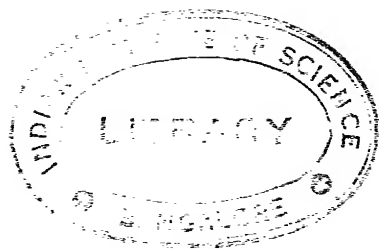


# An Introduction to the Study of Ore Deposits



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BY

F. H. HATCH, O.B.E., PH.D

MEM. INST. CIVIL ENGINEERS; PAST-PRESIDENT INST. MINING  
AND METALLURGY; PAST-PRESIDENT GEOL. SOC. OF S. AFRICA,  
ADVISER ON METALLIFEROUS MINING TO THE MINES DEPARTMENT

LONDON

George Allen and Unwin Ltd  
MUSEUM STREET

1929

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UNWIN BROTHERS LTD., WOKING

FIRST PUBLISHED IN 1929





## PREFACE

THIS little book is founded on a course of lectures given at the request of the late Professor T. McKenny Hughes at Cambridge in the years immediately preceding the war. The vast amount of work that has since been done on ore deposits has of course necessitated a complete revision of the original lecture notes to bring them into line with modern views.

The historical summary of the theories of ore deposition, which forms the subject of the opening chapter, is based on a Presidential Address given to the Institution of Mining and Metallurgy in the year 1912, the additions necessary to bring it up to date having been made. The original sources of information are given in this chapter; but the remaining chapters have not been overburdened with references to the literature.

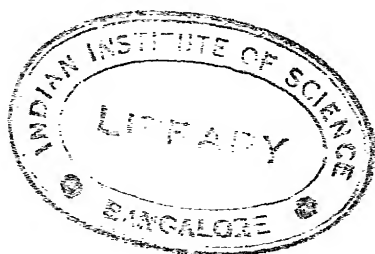
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of Mining and Metallurgy, the American Institute of Mining and Metallurgical Engineers, the Editor of *Economic Geology*, Messrs. John Taylor & Son, Professor R. C. Daly, Professor W. H. Emmons, Professor J. E. Spurr and others, acknowledgment of which is made in the explanatory text. The author has also to thank Mr. A. G. Brighton, B.A., of Christ's College, Cambridge, for some original drawings and Dr. Rastall for his careful revision of the proofs.

F. H. HATCH

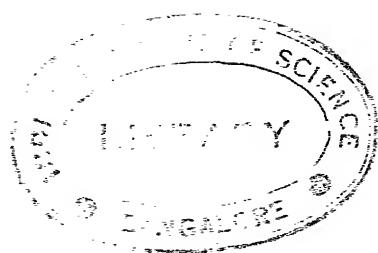
THE ALBANY, PICCADILLY

*January 1929*



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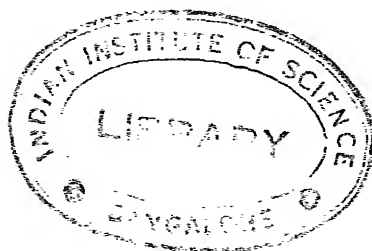
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# AN INTRODUCTION TO THE STUDY OF ORE DEPOSITS

## CHAPTER I

### HISTORICAL SUMMARY OF THE THEORIES OF ORE GENESIS

PRIOR to the sixteenth century the metallic content of ore veins was supposed to be a function of their orientation in regard to the planets. Agricola<sup>1</sup> (1494-1555) appears to have been the first to formulate a reasonable theory of ore genesis. Reduced to its simplest terms, this was that ore veins had originated by the deposition of minerals from solution in erosion channels (*canales*). The solutions, or juices (*succi*), as Agricola terms them, were assumed to be of meteoric origin and, under the influence of heat, to have taken mineral matter into solution.

From the time of Agricola to the end of the eighteenth century nearly all the contributors to the subject were Germans writing on the mines of Saxony and the Harz. The more important authors are Roesler, Becher, Henkel, Hoffmann, Zimmermann, von Oppel, Gerhard, Lasius, von Charpentier and von Treba.

Becher<sup>2</sup> and Henkel,<sup>3</sup> who wrote in the beginning

<sup>1</sup> George Agricola, *De Ortu et Causis Subterraneorum*, Basel, 1546.

<sup>2</sup> J. J. Becher, *Physica subterranea*, Leipzig, 1703.

<sup>3</sup> J. F. Henkel, *Pyritologia*, Leipzig, 1725, and *Idea Generalis de Lapidum Origine*, Leipzig, 1734.

of the eighteenth century, attributed the origin of ore-veins to the action on pre-existing stony and earthy matters of subterranean vapours arising from certain processes of "fermentation" in the bowels of the earth.

In 1749 Zimmermann<sup>1</sup> put forward a hypothesis which clearly had in it the germ of the modern theory of metasomatism. He ascribed the origin of veins to a transformation of the rocks into metallic minerals and their accompanying vein-stones, by the action of solvents that found a path through innumerable small rents and other openings in the rocks. Zimmermann applied his theory indiscriminately to explain the origin of all veins, including those that, by common agreement, are now considered to have been formed by the filling of fissures without replacement; and von Treba,<sup>2</sup> in supporting Zimmermann's view, insisted particularly on the far-reaching changes effected in rocks by circulating waters, especially when aided by heat. "I am persuaded," he wrote in 1785, "that there is constantly going on in our mountains a variety of transformations, compositions and decompositions, which not only take place at present, but will continue to the end of time."

According to Gerhard,<sup>3</sup> who wrote in 1781, waters circulating through the rocks adjacent to a vein become charged with certain of the metallic and earthy substances contained in them. Passing through the crevices and interstices of the rocks to the larger rents and fractures they deposit their mineral burden in cavities which, when filled, become veins. Lasius,<sup>4</sup> in his

<sup>1</sup> C. F. Zimmermann, *Obersächsische Bergakademie*, 1749.

<sup>2</sup> F. W. H. von Treba, *Erfahrungen vom Innern der Gebirge*, Dessau and Leipzig, 1785.

<sup>3</sup> C. A. Gerhard, *Versuch einer Geschichte des Mineral Reiches*, Berlin, 1781.

<sup>4</sup> G. S. O. Lasius, *Beobachtungen über die Harzgebirge*, Hanover (1789), p. 417.



description of the ore veins of the Harz, supported this view. It will be seen that it was a precursor of the more modern theory of lateral secretion.

To von Oppel<sup>1</sup> belongs the credit of having shown that mineral veins were largely the filling of fault-fissures, a principle which up to that time does not appear to have been sufficiently recognized.

At the end of the eighteenth century the mining world was dominated in all matters relating to ore genesis by the famous Freiberg professor, Abraham Gottlob Werner,<sup>2</sup> who insisted that all veins, including those that we now term "intrusive dykes," had resulted from the filling of contraction-fissures by means of the primeval universal ocean, which, according to the Wernerian doctrine, covered the globe and contained in solution all the necessary materials for the formation of its crust. These waters, descending from above into the fissures, deposited there the vein minerals by chemical precipitation.

This Neptunist view was, in the beginning of the nineteenth century, attacked, and finally overcome, by Hutton<sup>3</sup> and his Plutonist or Vulcanist school. Unfortunately, the Plutonists went too far in the other direction, in insisting that all ore veins were of igneous origin: "The materials," wrote Playfair,<sup>4</sup> "which fill the mineral veins were melted by heat and forcibly injected into the clefts and fissures of the strata."

But Hutton's broad generalization was soon discarded in favour of deposition from waters of meteoric origin. An animated discussion ensued and was maintained for half a century on the respective merits of the *descensionist*, *ascensionist* and *lateral secretionist*

<sup>1</sup> Von Oppel, *Essay on the Working of Mines*, circa 1749.

<sup>2</sup> A. G. Werner, *Neue Theorie von der Entstehung der Gänge, mit Anwendung auf der Bergbau*, 1791.

<sup>3</sup> James Hutton, *Theory of the Earth*, Edinburgh, 1795.

<sup>4</sup> J. Playfair, *Illustrations of the Huttonian Theory*, Edinburgh, 1802.

theories; or, in other words, whether the mineral burden of the circulating waters instrumental in vein-formation was derived from superficial rocks, from deep-seated sources, or from the wall-rocks of the veins themselves.

Gerhard's suggestion that the mineral contents of veins were derived from the adjacent country-rock by aqueous leaching remained a mere hypothesis until the middle of the nineteenth century, when lateral secretion was put forward as a reasoned theory by Bischof.<sup>1</sup> The work of this chemist and that of Dieulafait<sup>2</sup> and Sandberger<sup>3</sup> was directed to establish two important facts: (1) that the gangue of ore veins varies in correspondence with the wall-rock; and (2) that the heavy metals occur in minute traces in certain of the igneous and sedimentary rocks constituting the "country" of ore veins; but practical work in the Przibram mining districts of Bohemia did not lend support to the theory, and F. C. v. Beust's<sup>4</sup> study of the lead-zinc veins of Saxony (1840-50) and the work of Theodor Scheerer<sup>5</sup> on the same district (1862) showed that they had been filled by thermal solutions bringing mineral matter from below. This view of ore genesis was supported by the subsequent work of A. Patera,<sup>6</sup> A. W. Stelzner,<sup>7</sup> F. Posepny,<sup>8</sup> and van Hise.<sup>9</sup> These authors argued that the ground-

<sup>1</sup> K. G. Bischof, *Physical and Chemical Geology*, 1846-7.

<sup>2</sup> L. Dieulafait, *Comptes rendus*, 89. (1879), p. 453; *ibid.*, 90. (1880), p. 1573; *ibid.*, 93. (1881), p. 804; *ibid.*, 96. (1883), pp. 70, 125, 164 and 178.

<sup>3</sup> F. v. Sandberger, *Untersuchungen über Erzgänge*, Wiesbaden, 1. (1882); 2. (1885).

<sup>4</sup> F. C. v. Beust, *Kritische Beleuchtung der Werner'schen Gangtheorie*, Freiberg, 1840; *Die Erzgangzüge im sächsischen Erzgebirge*, Freiberg, 1856.

<sup>5</sup> T. Scheerer, *Zeitsch. d. deutsch. geol. Gesell.*, 14. (1862), pp. 78-94.

<sup>6</sup> A. Patera, *Verh. der k.k. geol. Reichsanst.* (1888), p. 223.

<sup>7</sup> A. W. Stelzner, *Zeitsch. d. deutsch. geol. Gesell.*, 31. (1879), p. 644.

<sup>8</sup> F. Posepny, *Zeitsch. f. prak. Geol.* (1896), p. 377.

<sup>9</sup> C. R. van Hise, *Trans. Amer. Inst. Min. Eng.*, 27. (1892), p. 197-369; *ibid.*, 30. (1900), p. 27; *ibid.*, 31. (1902), p. 282.

water (originating by precipitation from the atmosphere) descends by capillarity through the interstices of the rocks to deep-seated regions, acquiring thus a high temperature and pressure and, consequently, a vastly increased solvent power, whereby in its passage through the rocks it is enabled to take up certain of the mineral substances there disseminated in a minute form. Moving laterally it ultimately reaches open conduits, through which it ascends, depositing its mineral burden as temperature and pressure fall.

In recent years there has been a reaction to igneous views, in which the Swedish geologist, J. H. L. Vogt,<sup>1</sup> has played a leading part; other exponents being J. F. Kemp,<sup>2</sup> W. H. Weed,<sup>3</sup> W. Lindgren,<sup>4</sup> J. E. Spurr,<sup>5</sup> W. H. Emmons,<sup>6</sup> W. H. Goodchild,<sup>7</sup> R. H. Rastall,<sup>8</sup> and P. Niggli.<sup>9</sup> Certain classes of ore deposits are held to have been formed by a differentiation of igneous magmas prior to consolidation; and the important rôle of metalliferous emanations recognized by Élie de Beaumont,<sup>10</sup> Daubrée,<sup>11</sup> and Durocher<sup>12</sup> in the years 1840-50 to explain the origin of tin-ore deposits has been amplified and extended to other metalliferous deposits. Certain *agents minéralisateurs*, such as fluorine,

<sup>1</sup> J. H. L. Vogt, *Zeitsch. f. prakt. Geol.* (1893, 1894, 1895), and *Econ. Geol.*, 21. (1926), p. 207.

<sup>2</sup> J. F. Kemp, *Trans. Amer. Inst. Min. Eng.*, 31. (1901), pp. 169-198; 33. (1903).

<sup>3</sup> W. H. Weed, *Trans. Amer. Inst. Min. Eng.*, 33. (1903), p. 715.

<sup>4</sup> W. Lindgren, *Posepny vol.*, *Trans. Amer. Inst. Min. Eng.* (1901), 611.

<sup>5</sup> J. E. Spurr, *U.S. Geol. Surv. Ann. Rep.*, 18. Pt. 3 (1898), pp. 87-392; *Econ. Geol.* 2. (1907), pp. 781-795; *ibid.*, 7. (1912), pp. 485-492; *ibid.*, 18. (1923), p. 617; *The Ore Magmas*, New York, 1923.

<sup>6</sup> W. H. Emmons, *Econ. Geol.* 3. (1908), pp. 611-627; *Trans. Amer. Inst. Min. Met. Eng.*, 74. (1926), p. 29.

<sup>7</sup> W. H. Goodchild, *Trans. Inst. Min. Met.*, 28. (1917), pp. 12-58.

<sup>8</sup> R. H. Rastall, *Geol. Mag.*, 82. (1920), pp. 290-299, and *ibid.*, 85. (1928), pp. 270-279.

<sup>9</sup> P. Niggli, *Abhand. zur prakt. Geol.*, 1. (1925), p. 1.

<sup>10</sup> Élie de Beaumont, *Bull. Soc. géol. de France* (1847), p. 1249.

<sup>11</sup> A. Daubrée, *Annales des Mines*, 20. (1841), p. 65.

<sup>12</sup> J. M. E. Durocher, *Comptes rendus*, 28. (1849), p. 607.

chlorine, sulphur, phosphorus, silicon and boron, have the property of forming with the metals volatile compounds which escape from the granite magma as gases with low critical temperatures (the *aura granitica* of Elie de Beaumont). These compounds ascend through already formed fissures in the overlying rocks, or force their own passage by attacking the minerals that compose them. But even here water is all-important as agent for ore concentration. Dissolved or occluded in some way in the molten magmas, it separates on the fall of temperature and pressure, and forms an extract containing those substances that are more soluble in water than in the silicate melt. Suess,<sup>1</sup> in an address on the Karlsbad springs, delivered in 1902, drew attention to the connection existing between thermal springs, vulcanicity and ore deposition. He applied the term *hypogene* or *juvenile* to thermal springs (like those of Karlsbad), which, originating in the depths of the earth's crust, bring water to the surface for the first time. Such hot springs are, in fact, the last survivors of vulcanicity, being the relics of a late stage of fumarole activity. Their mineral content comprises readily soluble compounds of the alkalies and alkaline earths, together with, and partly in combination with, sulphur, chlorine and carbon dioxide, the less soluble metallic compounds having already been deposited as ores at lower depths in the earth's crust. According to Suess, the after-products of eruption vary with the temperature: in the earlier (pneumatolytic) phases of emanation the gases are dry and their deposits (such as tin-ore and its accompanying boron, fluorine, tungsten and uranium minerals) are the products of sublimation. At a later period, strongly alkaline magmatic waters

<sup>1</sup> E. Suess, *Verh. Ges. deutsch. Naturf. u. Aertze*, Karlsbad, 1902; see also *Das Antlitz der Erde*, 3. (1909), p. 630; and compare A. Gautier, *Annales des Mines*, 9. (1906), p. 316.

are given off, and to these are attributable the sulphide and arsenide phases of vein formation, e.g., the deposition of iron-pyrites, chalcopyrite, primary bornite and chalcocite, enargite, galena, blende, etc.

Waters of meteoric origin, if they are not the main agents of deposition for the primary sulphide ores, are undoubtedly the formative agents for a considerable number of ore deposits, including the products of oxidation, chlorination and reduction above the permanent water-level, and the secondarily enriched ores usually found near the junction of the zone of oxidation with the zone of primary sulphides. So important are the functions of these waters in dissolving and redepositing at a lower level the ores of copper in a concentrated form, that it has been confidently stated that the bulk of the copper production of the world was not alone in the past, but is also at the present time drawn from the zone of secondary enrichment.<sup>1</sup>

It will be seen from the above review how much at variance are even the most capable workers in this field. As a recent writer<sup>2</sup> has pointed out: "It seems probable that the most rational theories are true in particular, even if exceptional, cases; and some are undoubtedly true in all cases. But invariably the zealous advocate of conceptions of ore genesis widens his field too far, and those who put his conceptions to the test find inevitable contradictions."

As regards the classification of ore deposits, writers in the past were constrained, in view of the lack of data, to ignore the genetic principle and to base their classifications on form alone; thus in the earlier classifications, e.g. those of B. von Cotta<sup>3</sup> (1853) and

<sup>1</sup> J. Douglas, *Trans. Amer. Inst. Min. Eng.*, **19**. (1891), p. 693; R. A. F. Penrose, *Journ. Geol.*, **2**. (1894), p. 288.

<sup>2</sup> E. V. Dougherty, *Econ. Geol.* (1928), p. 573.

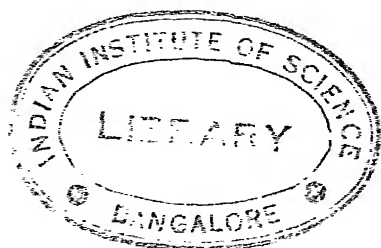
<sup>3</sup> B. von Cotta, *Die Lehre von den Erzlagertstätten*, Freiberg, 1859.

J. Grimm<sup>1</sup> (1869) there was no reference to ore genesis. A von Groddeck<sup>2</sup> (1879), in distinguishing cavity fillings from metasomatic replacements, first introduced the genetic principle. Now it is the basis of ore classifications. Lindgren,<sup>3</sup> for example, has, with a considerable measure of success, founded a classification on the physical conditions (temperature and pressure) prevailing during ore formation.

<sup>1</sup> J. Grimm, *Die Lagerstaetten der nutzbaren Mineralien*, Prague, 1869.

<sup>2</sup> A. von Groddeck, *Die Lehre von den Lagerstaetten der Erze*, Leipzig, 1879.

<sup>3</sup> W. Lindgren, *Mineral Deposits*, third edition, New York, 1828.



## CHAPTER II

### SOME GENERALITIES

AN ore may be defined as a mineral containing a useful metal in such chemical combination and in such quantity as to make its extraction profitable under the economic conditions prevailing, or likely to prevail in the near future. Ore deposits are concentrations formed in Nature by chemical and mechanical agencies. Although in some cases the immediate connection with igneous activity is not apparent, if traced back to their original source the metals in them will be found to have been derived in the first instance from the igneous rocks.

Some ore deposits are indubitably related to igneous rocks. Moreover, it has been clearly proved by the researches of Bischof, Dieulafait, Sandberger<sup>1</sup> and many others that the heavy metals (gold, silver, copper, lead, etc.) occur in minute traces in most igneous rocks; while, in addition to iron and aluminium, titanium, chromium, cobalt and nickel are almost invariably present, and in amounts easily determinable by chemical analysis, in basic igneous rocks, such as the peridotites, pyroxenites, gabbros, serpentines, etc. Sandberger's researches showed that the heavy metals are contained in the common ferromagnesian silicates (namely, the micas, hornblendes, and augites of the igneous rocks); and, further, that

<sup>1</sup> References already given, *see* p. 16.

small quantities of the heavy metals occur in the sediments of all ages, and especially in the slates of the older systems.

The metallic components of the igneous rocks are extracted and concentrated by the following agencies: 1, segregation by *differentiation* in molten magmas; 2, the escape from the latter of gases and vapours carrying volatile metallic compounds (*pneumatolysis*); 3, the circulation of hydrothermal solutions, whether of deep-seated or meteoric origin (*hydatogenesis*); 4, oxidation, hydration and solution in the *zone of weathering* and reprecipitation in the *zone of secondary enrichment*; 5, erosion and sedimentation; and 6, solution in the zone of weathering and bio-chemical precipitation in seas, lakes and swamps.

With regard to the nature of the deposits formed by these various agents the following general observations may be made. The magmatic segregations, occurring, as they generally do, on the margin of an igneous intrusion, have often the form of contact deposits; but since they remain an integral part of the igneous body from which they are derived, they are not contact deposits in the proper sense of the term, which should be restricted to ore bodies formed as a result of the metamorphism of the invaded rocks.

The ore bodies formed by gaseous (pneumatolytic) or hydrothermal (hydatogenetic) agents may be divided into two groups according to their relation to the enclosing rock: they either *fill cavities*, which may be openings of discission (joint-fissures, dislocation-fissures, saddles, etc.), openings of solution (caves, sink-holes, enlarged joints in limestone), or interstitial openings (pore-spaces in sediments or gas-pores in lavas); or they are *replacements* of some pre-existing mineral or rock. The deposits formed by chemical and mechanical agents are *detrital* and may be classified



as residual or eluvial, alluvial, and marine; while, lastly, those formed by bio-chemical agents are *beds of precipitation* in seas, lakes and swamps.

The form assumed by ore deposits is discussed in some detail in Chapter XI. As regards their mineral composition, it is necessary in the first place to distinguish between the *ore* and the *gangue*, the latter being the name given to the minerals that accompany the ore.

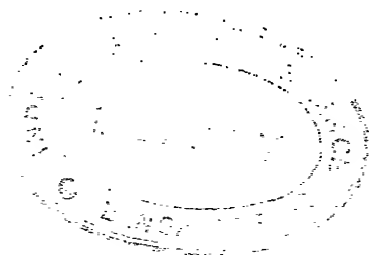
In the deep-lying part of a deposit, or what is often called the *primary sulphide zone*, the ore-forming metals occur in combination with sulphur, tellurium, arsenic and antimony (as sulphides, tellurides, arsenides and antimonides of one or other of the metals—gold, silver, copper, mercury, lead, vanadium, zinc, nickel, cobalt), or as silicates (of iron, manganese), or oxides (of iron, tin, chromium). Occurrence in the native state is in this zone confined to a few of the metals (gold, platinum, iridium, palladium, etc.).

In the upper portion of the deposit, in the *zone of oxidation*, the metals occur as carbonates, sulphates, phosphates, arseniates, antimoniates, chromates, silicates, chlorides, oxychlorides and hydrates. Where special conditions involving strong reduction have prevailed certain metals may appear in the native state (copper, silver, mercury).

The commonest *gangue minerals* in the deeper parts of deposits are quartz and the sulphides of iron (pyrites, marcasite, mispickel). Nearer the surface the hydrated forms of silica (opal, etc.), the carbonates of iron, calcium, barium and magnesium (siderite, calcite, aragonite, ankerite, dolomite) and the sulphates of calcium and barium (gypsum, anhydrite, barytes) are common.

Important deductions as to the origin of an ore deposit can be drawn from the nature of its mineral

associates, always provided that care is taken to distinguish between the different epochs of mineralization, i.e. to say whether the mineral in question is primary or secondary, having been in the latter case introduced at a later date from without, or derived from the primary mineral by the chemical action of permeating solutions. Thus, for example, the presence of heavy anhydrous iron oxides or silicates, such as magnetite, hedenbergite (a pyroxene), fayalite (an olivine), ilvaite (an epidote) and knebelite, indicates a deep-seated origin at high temperatures; the presence of fluorine-, boron-, and phosphorus-bearing minerals, such as fluorspar, apatite, tourmaline and axinite, indicates, further, that the chemically active elements known as *mineralizers* assisted extraction and deposition at high temperatures. On the other hand, hydrated minerals, such as chlorite, opal and members of the zeolite group point to an origin near the surface, since their formation is only possible at a comparatively low temperature. The association of minerals belonging to the same epoch of formation is connoted by the term *paragenesis*.



## CHAPTER III

### ORE FORMATION BY DIFFERENTIATION IN BASIC MAGMAS

WE know that below the crust of the earth there are igneous magmas, which by upward penetration give rise to large plutonic intrusions such as bathyliths and laccoliths, or to minor intrusions such as sills and dykes. The concentration by differentiation of the metalliferous compounds contained in these *silicate melts* produces ore bodies which are associated with plutonic rather than with minor intrusions, since the slower cooling of the larger bodies offers greater facility for such concentration.

These magmas are either of a basic (basaltic) or of an acid (granitic) type. The former will be considered first, the ore bodies connected with the granitic type forming the subject of the next chapter.

A marginal segregation of the heavier minerals during the cooling of a basic silicate melt is brought about either by *fractional crystallization* and gravitation of the crystals, or by *liquation*, the latter being a separation into two immiscible fluids, the heavier of which sinks to the bottom of the magma basin.

The density increases with the number of molecules of metallic oxides such as those of iron, chromium, nickel, copper, calcium, magnesium. Hence these molecules will be more abundant in the lower than in the upper portion of a magma basin. In general, therefore, the net result is the formation of a lower basic zone

and an upper more acid (that is, siliceous) portion. As exposed by denudation, the ores are found as a rule in the peripheral portion of the out-cropping mass, although, exceptionally, they occur as a local concentration in the heart of the igneous mass itself. Such local segregations, termed *Schlieren* by the Germans, owe their origin to differentiation prior to eruption.

Examples of magmatic differentiation are certain titaniferous iron-ores in basic eruptives (e.g. Ekersund-Soggendal in Norway, Taberg and Routivara in Sweden, and the Bushveld complex of the Transvaal); chromite in ultra-basic eruptives (e.g. in New Caledonia, in the Bushveld complex of the Transvaal, and in Rhodesia); and primary platinum in basic and ultra-basic rocks (e.g. Nischnie Tagilsk and Mount Solovief in the Urals, and in the Bushveld complex). The nickeliferous pyrrhotite of Sudbury in Ontario and Insizwa in Griqualand and the pyrite deposits of Røros and Sulitjelma in Norway are also generally held to have originated by magmatic differentiation.

The iron-ore deposit of Taberg in Småland (Sweden) has been described by Sjögren, Törnebohm and Vogt as consisting mainly of titano-magnetite and olivine, together with a small quantity of biotite and a strongly basic feldspar. It is found in the centre of a mass of olivine-hypersthene or norite, into which it passes by insensible gradations. The area occupied by the olivine-hypersthene together with the magnetite-olivine is elliptical in form and measures about one mile by one-third of a mile. Its vertical extent is unknown but must be considerable. The ore body is a *Schliere* of basic material formed by concentration in the deeper portion of the magma basin before eruption, molecular diffusion without the actual separation of minerals being the operating cause.

A slightly different case is presented by the ilmenite deposits of the Ekersund-Soggendal district, of which that of Storgangen may be taken as a type. This

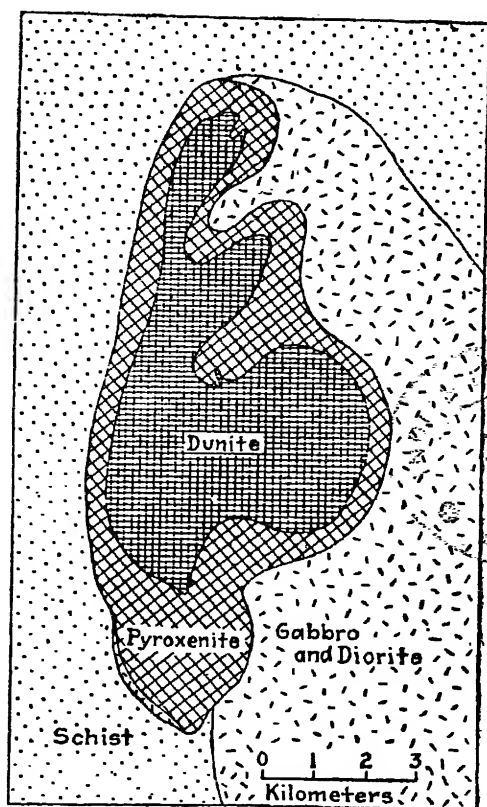


FIG. 1.—Geological map of the platinum-bearing district of Tagilsk in the Urals, showing concentric shells of igneous rock produced by magmatic differentiation after intrusion into the schists.—After Duparc and Tikonowich.

deposit occurs as a dyke, three kilometres long and 20 to 70 metres wide, traversing labradorite rock (a norite, extremely poor in ferro-magnesian constituents). The dyke itself consists of ilmenite, hypersthene and

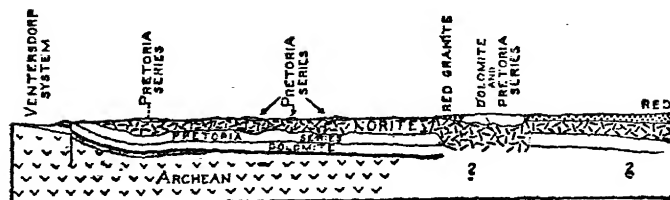
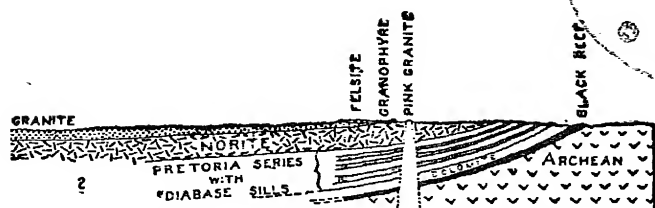


FIG. 2.—Section (east-west) through the Bushveld Complex, showing and Archaen. Scale 1:

labradorite, and is in fact an ilmenite-norite with an average ilmenite content of 40 per cent., rising in places to as much as 80 per cent. At Bläfsjeld the ilmenite predominates to such an extent that the rock loses its norite character altogether and consists of 90 per cent., or even 95 per cent., of the iron-ore. In all cases the dykes are separated from the labradorite rock by sharp boundaries; here again, therefore, the magmatic differentiation must have taken place before eruption.

The differentiation of a silicate-sulphide magma into a lower sulphide fraction (as in matte smelting) and an upper silicate portion (the slag) is illustrated by the Sudbury and Insizwa occurrences.

At Sudbury in Ontario, Canada, a single sheet of norite or gabbro has been intruded between Upper and Lower Huronian sediments. This sheet, together with the sediments in which it lies, has been folded into a basin, the greatest diameter of which is about 36 miles and the shortest 16. The sheet is about  $1\frac{1}{4}$  miles thick, and in the deepest part of the basin is covered by about 2 miles of sediments. Cooling took place slowly under this heavy cover, and the magma separated into an upper acid layer and a lower basic layer, the nickel-bearing iron sulphide, which crystallized as the mineral pyrrhotite ( $\text{FeS}$ ) with associated pentlandite ( $\text{NiS}$ ), being concentrated along the lower



the relation of the red granite, norite, Pretoria series, Dolomite 3,000,000.—After R. A. Daly.

margin. Other associated minerals are chalcopyrite ( $\text{CuFeS}_2$ ), and a small amount of the platinum arsenide, sperrylite ( $\text{PtAs}_2$ ).

Coleman,<sup>1</sup> the chief supporter of the magmatic separation theory for the origin of the Sudbury ore bodies, gives the following arguments in its favour. The ores are everywhere associated with a single eruptive sheet of norite; no ore occurs without norite; no long stretch of the marginal, that is to say lower, zone of the norite is entirely devoid of ore. Norite and ore are mixed in every proportion, there being a gradation from a rock containing scattered particles of ore through an aggregate, in which ore and rock are present in equal amounts, to an almost pure ore with a few rock-forming minerals scattered through it. Fresh norite occurs close to the ore bodies and is often impregnated with ore. No considerable amount of rearrangement by water could have taken place without changing so susceptible a mineral as hypersthene into secondary products. The rocks which lie below the intrusive sheet contain no ore; while the ore and norite are not separated by any definite bounding wall, mining work being stopped in that direction only when the mixture of ore and rock becomes too poor to exploit. There is no banding (*crustification*) such as characterizes cavity-filling (see p. 51), and

<sup>1</sup> A. P. Coleman, *Journ. Geol.*, 15. (1907), pp. 757-782.

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such small quantities of quartz and calcite as occur are confined to veins of later formation.

As militating against the magmatic segregation theory other observers have drawn attention to the fact that some of the ore bodies, although occurring near the norite margin, are actually in acid rocks of later date than the norite, and that, moreover, the sulphides in these rocks occur as the cement of well-defined breccias, indicating crushing, shearing and deposition by hydrothermal agencies. Such ore bodies are considered to have been deposited by solutions

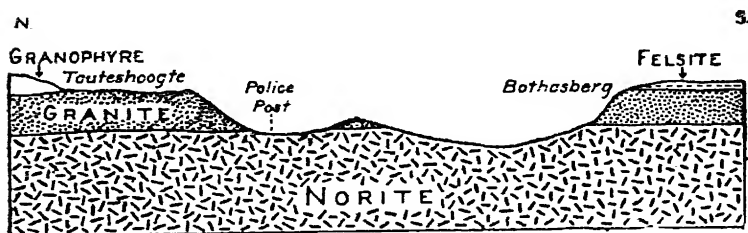


FIG. 3.—Section showing relation of the norite to the red granite, Bushveld Complex, Transvaal (scale 3·5 miles to the inch).—After A. L. Hall, *Rep. Geol. Surv. Union of S.A.* (1910).

emanating from the same magma reservoir as the norite, but at a later date than the eruption of the latter. This does not, of course, preclude the origin of some of the ore bodies by differentiation of the norite magma during its cooling *in situ*. There is no reason to postulate the same origin for all the ore bodies, more especially as they show varying geological relations.

At Insizwa in Griqualand East the magma in cooling has differentiated into the following products: gabbro with a little quartz at the top of the basin through olivine-gabbro to picrite. At the base occurs the sulphide fraction, consisting of a mixture of pyrrhotite,



pentlandite and chalcopyrite, together with some nickel, platinum and gold. The solid sulphide is a bed two feet thick, but it passes upward into a zone of mineralized picrite.

Fine examples of direct segregation from an igneous magma are found in the Bushveld Igneous complex of the Transvaal. This is the name given to a mass of intrusive igneous rocks occupying an area of 280 miles from east to west and 160 miles from north to south in the central part of the country. It rests on a floor

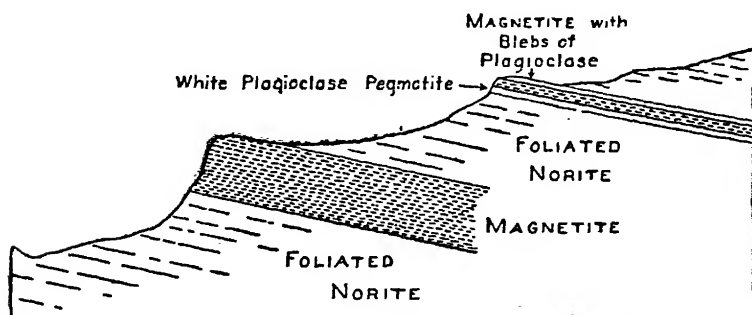
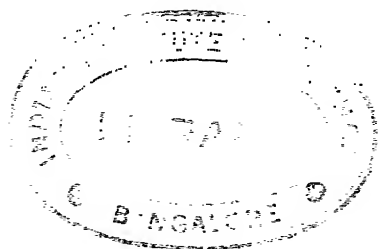


FIG. 4.—Section showing beds of magnetite in norite, Magnet Heights, Bushveld Complex, Transvaal (scale 24 feet to the inch).—After A. L. Hall, *Rep. Geol. Surv. Union of S.A.* (1909).

of the lower members of the Transvaal system and is covered by a roof of the Rooiberg series. A great variety of rock types, ranging in composition from acid to ultra-basic, compose it, a soda-rich granite being found in the central and upper portions, and norite with subordinate anorthosite and pyroxenite in the peripheral and lower portions. In all probability they are differentiates of a common magma, the earliest consolidation being that of the basic rocks, together with deposits of titaniferous iron-ore and chromite. These deposits take the form of more or less persistent sheets following one or more horizons in the great norite zone, which, with a dip of 5 to 30 degrees

towards the centre of the complex, can be traced round its periphery. The chromite horizons occur near the base of the norite; immediately above them is a zone of platinum-bearing norite; while the beds of titaniferous iron-ore occur near the top of the norite and are associated with layers of anorthosite. The order in which the minerals occur from below upwards is no doubt that of their crystallization from the parent magma. It is possible that the titaniferous iron-ores were precipitated from iron and titanium-bearing gases that accumulated in the upper part of the magma while it was undergoing gravitation-differentiation.



## CHAPTER IV

### ORE FORMATION BY GASEOUS EMANATIONS FROM GRANITIC MAGMAS

THE word "granitic" is used here to cover intrusives more acid than diorite, i.e. quartz-diorites, monzonites, granodiorites and granites. It is a matter of common observation that the great bulk of lode deposits are found in the neighbourhood of these rocks, and there can be little doubt that they are derived from a magma of a more or less uniform type.

Such an undifferentiated magma may be considered as a solution containing, among other constituents, a certain amount of water and the chemically active elements boron, fluorine, chlorine, phosphorus, sulphur, tellurium, etc., which are sometimes spoken of as *mineralizers*, since they possess the property of forming volatile compounds with the heavy metals. As the magma cools it splits up into differentiates of varying composition; and consolidation of the different fractions takes place in the order of decreasing viscosity, the residuum containing an excess of silica, a portion of the alkalis, practically all of the water and compounds of the metals tin, tungsten, molybdenum, uranium, lead, copper, iron, and many of the rarer metals.

In the early stages of consolidation, cracks and fissures are formed in the cooling crust, into which the residual liquid fractions of the magma are injected. The earliest injections give rise to dykes of quartz-porphyry

and micro- or crypto-granite; later extracts solidify as pegmatites and aplites; while the most acid extract of all consolidates as almost pure quartz. While the temperature is still high, i.e. before it has fallen below the critical temperatures of the acid vapours, a proportion of the latter escape from the magma and deposit their mineral burden, either in fissures in the solidified crust of the igneous mass itself or in the surrounding sediments, to which they gain access through bedding planes, joints, faults, crush zones, and even by attack-

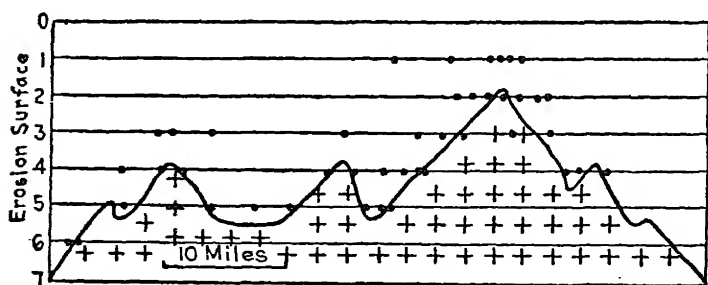


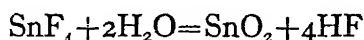
FIG. 5.—Cross-section of ideal bathylith showing by dots the most favourable position for lode deposits, and by lines six stages of erosion.—After W. H. Emmons, *Trans. Amer. Inst. Min. Met. Eng.*, 74. (1926), p. 32.

ing and replacing their component minerals. This process is generally spoken of as *pneumatolysis*.

A typical example of pneumatolysis is the formation of the ores of tin and other metals in the neighbourhood of granite, as in Malaya, Saxony and Cornwall. The ore-deposits are found chiefly in the invaded sediments or in the marginal portions of the bathyliths, in their satellite cupolas, their roof-pendants, or in the dykes directly connected with them; while the interior of the granite masses are, as a rule, barren. The most favourable positions for ore occurrence are shown in Fig. 5, which is a diagrammatic cross-section of a bathylith undergoing erosion. The location of many of the more

important mines of Cornwall around the small granite cupolas, Carn Brea and Carn Marth, near and north of the main Carn Menellis granite, which itself is singularly free from lode deposits, is a well-known illustration of the principle just stated.

In tin deposits the chief ore is the oxide— $\text{SnO}_2$  (cassiterite)—and it is probably derived from the granite in the form of fluoride of tin ( $\text{SnF}_4$ ), a volatile compound which, emitted at a high temperature, decomposes at a lower temperature in the presence of water vapour to a dioxide of tin, as shown by the following equation:



A number of pneumatolytic changes accompany the formation of tin deposits. Such are silicification, greisenization, kaolinization, tourmalinization, axinitization, garnetization, etc.

*Silicification* of the walls of tin lodes is a common phenomenon, the resulting rock being either a mass of quartz and tourmaline with some cassiterite or a mixture of quartz with either chlorite or tourmaline. The Cornish miners give the name “capel” to the former and “peach” to the latter, the “capel” being usually green and the “peach” purple in colour. The silica is in part derived from the acid extract of the granite magma, in part from the kaolinization of the felspar of the granite. The chlorite is derived from the alteration of biotite—also a constituent of the granite.

The metasomatic alteration product of granite, known as *greisen*, is a frequent associate of tin ores. The walls of the lodes frequently consist of this substance, and in some cases the deposit is a mass of greisen interlaced with small veins of tin ore (see Fig. 7). In greisen the felspar of the original granite is replaced by quartz, blue tourmaline, muscovite, topaz, or even by cassi-

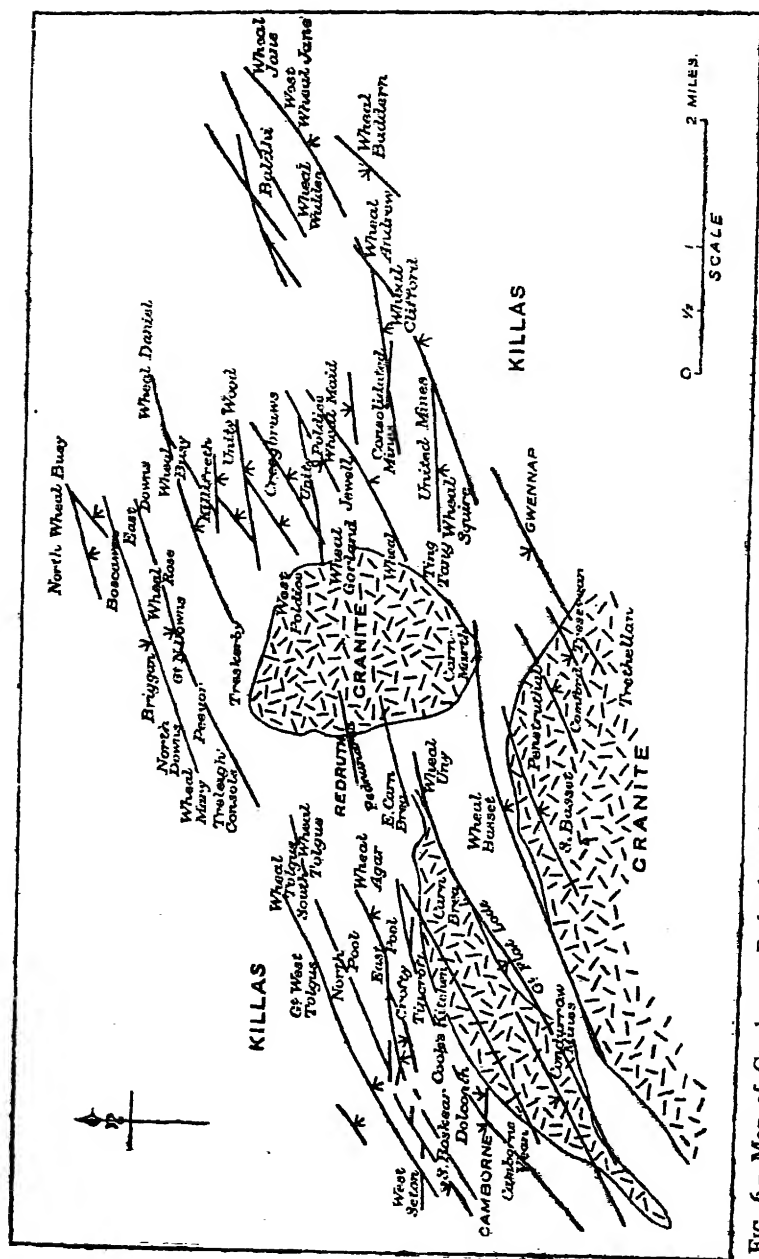


FIG. 6.—Map of Camborne, Redruth and Scorrier mining districts in Cornwall showing the relation of the lodes to the granite and the killas (slates).—From *Special Rep. Geol. Surv. of Gt. Britain*, 27. (1923), p. 17.

terite; at the same time biotite is altered to chlorite and to brown tourmaline.

The replacement of the felspar of the granite by a mixture of kaolinite and quartz in the process known as *kaolinization* is also common. Orthoclase has the composition represented by the formula:  $K_2O \cdot Al_2O_3 \cdot 6SiO_2$ ; kaolinite the composition:  $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ . The reaction, therefore, is one of hydration and removal

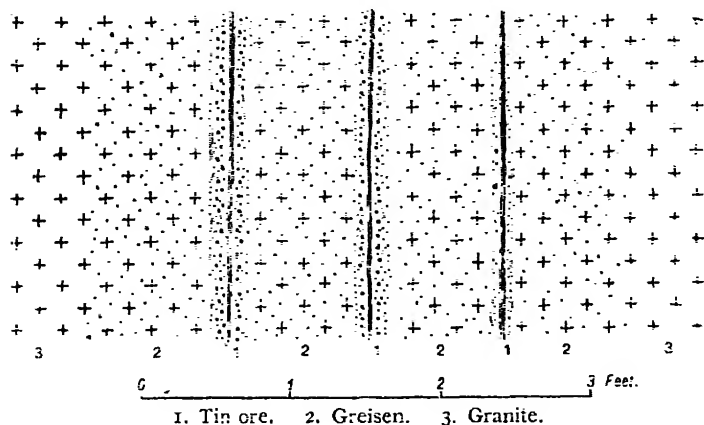
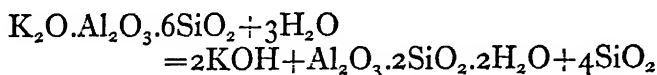


FIG. 7.—Diagrammatic section showing the formation of greisen on the walls of tin veins.—From *Memoir No. 16, Union of S.A. Geol. Surv.*

of the alkali and a part of the silica, and may be expressed by the following equation:



The mineral composition of the rocks within the aureole of metamorphism of the bathylith is also profoundly modified by the highly heated soluble constituents of the magma. Among the sediments the aluminous (shales and slates) and the calcareous (limestones) are the most subject to change. The aluminous

rocks develop tourmaline, sillimanite, staurolite, andalusite and topaz, all silicates of alumina, while the calcareous rocks yield garnet, axinite, wollastonite, diopside, scapolite, vesuvianite and epidote, all lime-bearing silicates.

Tourmaline is a hydrated boric fluor-silicate chiefly of aluminium, and *tourmalinization* is brought about by the action of boric vapours either on the biotite or felspar of granite or on argillaceous sediments in contact with granite. When the granite is affected, the felspar phenocrysts, while retaining their original shape, have their substance replaced by quartz, tourmaline, apatite and muscovite. The felspar and brown mica of the groundmass are also replaced by tourmaline and quartz. Tourmalinized granite of this character is locally known as *schorl rock*. The tourmalinization of the argillaceous portions of the sediments in the aureole of metamorphism around granite intrusions is a common phenomenon, and such tourmalinization is especially characteristic of tin veins. Where the boric vapours traversed alternating beds of argillaceous and siliceous sediments, the argillaceous layers are tourmalinized, while the siliceous layers remain unaffected. Where, on the other hand, they traversed calcareous sediments, or basic lavas containing lime-felspars, axinite (a boro-silicate of lime and alumina) is produced in preference to tourmaline. The lime-garnet (grossularite) and lime-iron garnet (andradite— $3\text{CaO} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2$ ) are also largely formed in limestones and lime-bearing lavas.

The tin deposits are further characterized by the presence of the fluorine-bearing minerals—fluorspar (fluoride of calcium) and topaz (a fluoride and silicate of aluminium)—whilst among metallic compounds are found wolfram (a tungstate of iron and manganese), ilmenite (a titanate of iron), and various sulphides and



arsenides of copper, iron, lead and silver. Some of these compounds often constitute valuable ore deposits of the respective metals. For instance, in Cornwall copper ore occurred in such quantities in the upper portions of the lodes mined to-day exclusively for tin as to have made that county in the early part of the nineteenth century the world's chief producer of the metal. The Dolcoath mine at Camborne, which in recent years has been worked for tin alone, in former years produced copper to the value of £3,500,000, the two metals being derived from different horizons of the same lode. This depth change in mineral content is a function of the temperature and pressure of the ascending mineral-bearing fluids and is sometimes referred to as the *zonary distribution of ores*. Experience has shown that the order of metal occurrence in the Cornish lodes, from below upwards, is tin, tungsten, arsenic, copper, zinc, lead, silver, and this is the order of increasing solubility of the compounds of these metals in the ascending magmatic fluids.

The so-called *porphyry copper* deposits of the Western States of America (Arizona, New Mexico and Utah) are excellent examples of deposits found in the neighbourhood of bathyliths, the copper ores occurring mainly in limestone at its contact with intrusive monzonite and quartz-porphyry. In the Morenci district of Arizona they are found in Palæozoic limestone at its contact with a quartz-monzonite-porphyry, and in the latter itself. The principal contact minerals are garnet (andradite) and epidote. The primary ores are cupriferous pyrites and zinc-blende, while the high-grade copper sulphide—chalcocite—occurs in the zone of secondary enrichment. Near the surface leaching by meteoric waters has produced a barren zone.

At Bingham, Utah, copper and lead-silver ores occur in Carboniferous limestone and quartzite near their

junction with an intrusive monzonite-porphyry. Here the limestone is extensively marmorized with local

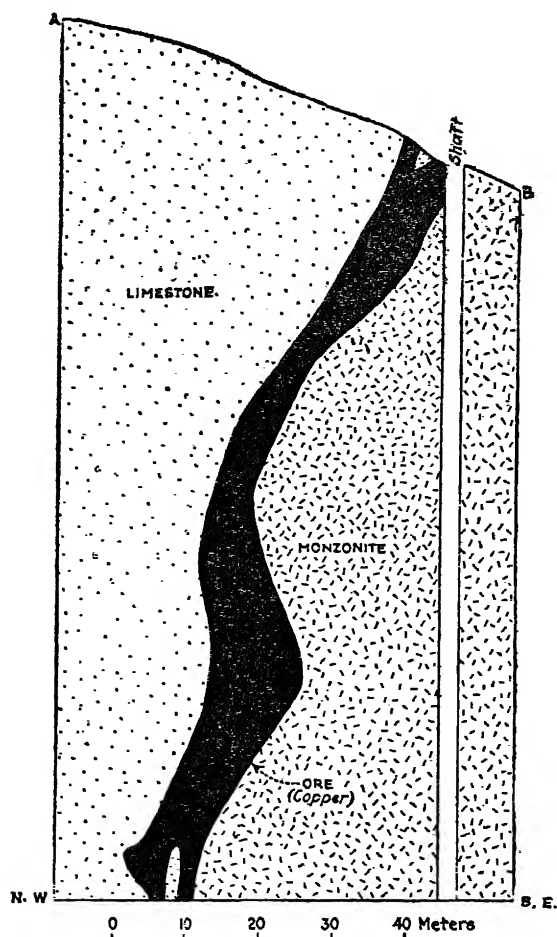


FIG. 8.—Cross-section of the Descubridora mine, Mexico, showing ore body at contact of monzonite with limestone.—After Spurr. *The Ore Magmas* (1923), p. 650.

replacement by pyrites and chalcopyrite. Disseminated sulphide copper ores (largely chalcocite enrichments) also occur in the porphyry itself.



At Bisbee, Arizona, Palæozoic limestones are cut by intrusions of a granite-porphphy thought to be of

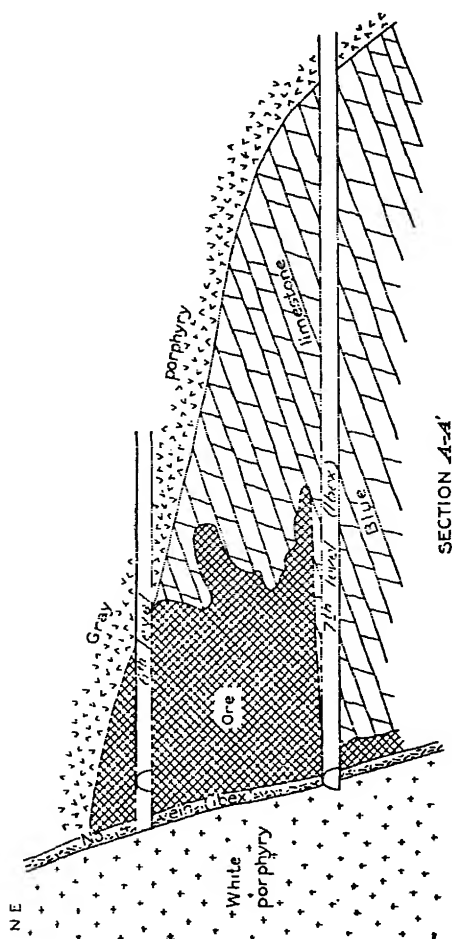


FIG. 9.—Cross-section showing the deposition of magnetite ore in limestone at its contact with porphyry at the Ibez mine, Colorado.—From *Professional Paper No. 148, U.S. Geol. Surv.*

Jurassic age. The limestone near the contact contains garnet, vesuvianite, diopside and tremolite. In the sulphide zone the ore bodies consist of pyrites, together with chalcopyrite and bornite. In the oxidation zone,

which is extensive, the primary ore is replaced by copper carbonates, cuprite and some chalcocite.

Copper lodes of similar origin, but in association with igneous rocks of a more basic type, occur on a great scale in Chile (e.g. the Braden deposit near Santiago). The vein-filling usually consists of pyrites, chalcopyrite, quartz and tourmaline, together with molybdenite and scheelite. This paragenesis points to a pneumatolytic origin and the indication is strengthened by the fact that the country rock is often tourmalinized and impregnated with pyrite.

Lead-zinc deposits in direct genetic connection with bathyliths occur in many parts of the world, e.g. in Bohemia (Przibram), Saxony (Freiberg), New South Wales (Broken Hill), and Burma (Bawdwin Mines).

Mention must also be made of the iron-ore deposits found at the contact of bathyliths with limestone. Magnetite is the principal ore mineral; hæmatite also occurs, but in smaller quantity. Accompanying iron silicates are olivine, garnet (andradite), pyroxene (hedenbergite) and ilvaite (a lime-iron silicate, allied to epidote). In the Banat (formerly a Province of Hungary) deposits of this character occur in limestone at its contact with Tertiary diorites and syenites. In the Kristiania district of Norway they occur in Silurian limestone in contact with granite and syenite or in xenoliths of limestone enclosed within the granite. In the island of Elba the deposits are at the contact of limestone with a Post-Eocene granite. The occurrence of well crystallized hæmatite is a feature of these latter deposits.



## CHAPTER V

### ORE FORMATION BY GASEOUS EMANATIONS CONNECTED WITH VOLCANIC ERUPTIONS

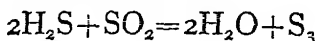
THE close connection of some ore deposits with volcanic activity is evident in all parts of the world. It is a matter of common observation that active volcanoes emit vast quantities of steam together with other volatile matter, both from their craters and from subordinate vents. The various types of the latter have received distinctive names: *fumaroles* are characterized by the escape of steam mixed with hydrochloric and hydrofluoric acids, *soffioni* by steam and boric acid ( $\text{H}_3\text{BO}_3$ ), *solfataras* by hydrogen sulphide and sulphur dioxide, and *mofetti* by carbon-dioxide and nitrogen.

The emission of carbon dioxide and hydrogen sulphide is continued long after the volcanoes have become inactive or dormant, these gases being abundant in volcanic regions where the volcanoes have not shown any other sign of activity within the memory of man. Warm springs carrying sodium carbonate, sodium chloride and silica in solution are also common in regions of expiring volcanism, as in the Auvergne (Central France), the Eifel (Germany), the Yellowstone Park (United States), Iceland and New Zealand.

The interaction of the gases given off from volcanoes leads to the deposition of minerals, which in some cases are of economic importance. Thus sulphur is of



frequent occurrence in volcanic districts and owes its origin to the following reaction:



Similarly borates are deposited by the soffioni; while chlorides and sulphates of copper, iron and other metals are found as sublimates near fumarolic and solfataric vents. The action of solfataric vapours on lavas rich in potash felspar produces the mineral alunite—a hydrated aluminium sulphate ( $\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 4\text{SO}_3 \cdot 6\text{H}_2\text{O}$ ), which in some districts (Italy, Nevada, Utah) is an important source of potash.

Opaline and chalcedonic silica are characteristic of the geyser deposits of certain volcanic districts (Iceland, Yellowstone Park and New Zealand); and many hot springs deposit great masses of calc sinter, or travertine, as in the Auvergne, in Tuscany and near Rome. Sometimes these volcanic deposits carry metallic minerals. Sulphur Bank in Lake County, California, is a case in point. Here cinnabar (sulphide of mercury) is found in association with sulphur, opal and chalcedony. Deposits of stibnite (sulphide of antimony) and realgar (sulphide of arsenic) from hot spring waters are other examples. Gold has also been recorded.

No doubt a considerable proportion of the exhalations from the magma basins which feed the eruptions becomes absorbed by the circulation of the ground-water, and the solutions thus formed, mingled possibly with waters of magmatic origin, give rise both in the lavas and in their adjacent formations to important deposits of gold, silver and quicksilver ores.

Numerous examples of such deposits occur in the great Tertiary volcanic ore province that borders the Pacific Ocean and extends from New Zealand and the East Indies through Japan and Southern Asia, South Europe, North-West Africa and the West Indies. It

includes the great Cordilleran region of the United States, Mexico and South America.

Some of the more important deposits situated in this ore province are the following:

Cripple Creek, Colorado—gold telluride deposits in phonolite lavas.

Tonopah, Nevada—gold-silver deposits in rhyolite and trachyte.

Comstock, Nevada—gold-silver deposits in andesite.

Guanajuato and Pachuca, Mexico—silver deposits in andesite.

Potosi, Bolivia—silver-tin deposits in rhyolite.

Redjang-Lebong, Sumatra—gold-silver deposits in andesite.

Thames and Waihi, Hauraki Peninsula, New Zealand—gold-silver deposits in andesite.

Silver-lead and gold-bearing deposits have been worked for centuries in andesites of Tertiary age in Hungary (Schemnitz, Kremnitz) and Transylvania. The latter district is characterized by the occurrence of gold tellurides (Offenbanya and Nagyag).

Characteristic of some of these deposits (Comstock, Tonopah, Potosi, Thames and Waihi, Hungary and Transylvania) is the *propylitic* alteration of the lavas with which they are associated. This is a process akin to solfataric action and results in the ferro-magnesian constituents being altered to chlorite and epidote, accompanying secondary products being carbonates of lime and magnesia, sericite, pyrites and marcasite. The rocks become of a dull-green colour, but there is little change in composition, the alteration consisting mainly of the addition of the water of hydration and a little sulphur.

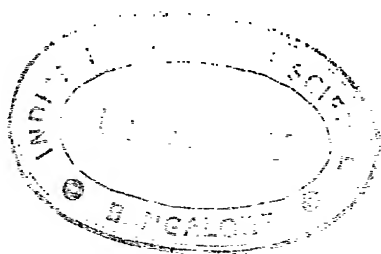
The connection of ore deposition with volcanic extrusions is, of course, not confined to those of

Tertiary age. Valuable deposits are associated with volcanic rocks of all ages.

Of especial interest in this connection are the copper deposits in basic lavas (basalt), and associated conglomerates of the Lake Superior region (Michigan). These rocks are pre-Cambrian and form a part of the Keweenawan series—the uppermost part of the Algonkian. They rest unconformably on Huronian beds, which in their turn unconformably overlie Archæan greenstones and schists.

The copper-bearing lavas are vesicular basalts. The copper occurs in the native form, particularly in the vesicles, together with calcite, epidote, chlorite and various zeolites. Pieces of the copper-bearing amygdaloid are found in the overlying conglomerates, showing that the filling of the vesicles must have taken place soon after eruption, and the presence of zeolites indicates a comparatively low temperature of formation. It is generally accepted that the mineralization is of the solfataric type, or, in other words, that it was produced by gaseous emanations following on the effusion of the lavas. During subsequent erosion copper was leached out of the lavas as copper chloride and concentrated in the porous beds by saline solutions. A reduction to the metallic state both in the lavas and in the conglomerates must have been brought about by some strong reducing agent, and Lane<sup>1</sup> lays stress on the presence of reducing carbon gases in the lavas.

<sup>1</sup> A. C. Lane in *Types of Ore Deposits* (1911), p. 186.





## CHAPTER VI

### ORE FORMATION BY THERMAL WATERS

WATER, on account of its mobility and solvent action, is the universal vehicle for the transference of mineral matter, and consequently for ore concentration. To a greater or less extent it takes all minerals into solution, especially at high temperatures and pressures; and its solvent action is much increased by the presence of acids or alkalies, according to the source from which it is derived. Its movement is governed, downward by the force of gravity, upward by heat and vapour pressure.

In the hydrothermal circulation the mineral-bearing solutions are no doubt in great part directly connected with igneous activity, namely in so far as they are formed by the cooling of the aqueous vapours given off at a late stage in the consolidation of igneous magmas (*see* p. 18). But surface waters (*i.e.* those that are meteoric in origin) also play an important, if subordinate, part; for by descending along fractures to a considerable depth they can acquire thermal properties either from the secular heat of the earth or by coming in contact with, or into the near neighbourhood of, igneous intrusions.

The conditions under which water exists and circulates in the crust of the earth must therefore be examined. Of the water that falls as rain, one part is the *run-off*—that is to say, water that reaches the rivers without having penetrated the surface. A second part is returned

into the atmosphere by *evaporation*; while a third part disappears into the soil and underlying rocks by *percolation*. Under the influence of gravity the water of percolation penetrates into the earth's crust, first through its superficial weathered and disintegrated layers, and then through the more solid rocks by way of fractures of jointing and faulting, planes of bedding, or the pore spaces between their constituent minerals.

It is a matter of common observation that at a variable depth below the surface there is a connected body of water which permanently fills all openings. The surface of this sea of water is called the *level of the ground-water*, or the *permanent water-level*, or, again, the *water-table*; it is the uppermost level of the belt of saturation.

Above the permanent water-level is the zone of percolation in which the openings in the rocks are only intermittently filled with water. This water is in active movement and air is present. The thickness of the zone of percolation varies greatly. At sea-level and at, or near, streams or lakes the level of the ground-water reaches the surface; in average areas it is from 10 to 100 feet below the surface; in high-lying districts with small rainfall it may be 100 to 300 feet below the surface, and in elevated desert regions as much as 1,000 to 2,000 feet below the surface.

The belt of saturation is divided by Finch<sup>1</sup> into two portions. The upper portion, or that part which has a means of horizontal escape and discharge, is named by him the zone of discharge. In general it lies between the water-table and sea-level. The waters in it have been termed *phreatic* (from the Greek *phreas*, a well), a term invented by Daubrée<sup>2</sup> and standardized by Daly.<sup>3</sup> In

<sup>1</sup> F. W. Finch, *Proc. Colorado Sci. Soc.*, 7. (1904), p. 193.

<sup>2</sup> G. A. Daubrée, *Les eaux souterraines*, Paris, 1887, Pt. i, p. 19.

<sup>3</sup> R. A. Daly, *Econ. Geol.*, 12. (1917), p. 495.

it their circulation is vigorous and extensive, as is evidenced by the vast volume of water discharged by springs.

The bottom part of the belt of saturation is the static zone. In it the waters are practically stagnant, or at best move very slowly. Near the bottom limit of the static zone the water gradually diminishes until the dry zone is reached. The boundary between these two zones is quite irregular, descending to great depth along fractures and rising high in solid ground. The lower levels of most deep mines are in the dry zone, and in some places this zone is reached at a depth of not more than 1,000 to 1,500 feet below the surface.

The waters circulating in the zone of percolation are cold, contain free oxygen, and are acid with dissolved carbon dioxide. Such waters have been termed *vadose* by Posepny.<sup>1</sup> They have a strong oxidizing effect on sulphides, pyrites, for instance, being decomposed with formation of oxide of iron and sulphuric acid. The net effect of the vadose circulation, therefore, is destruction, and the zone of percolation is practically coincident with the zone of weathering, although the latter overlaps the upper portion of the zone of discharge.

In the zone of discharge the waters, as they descend, lose their oxygen and carbon dioxide and deposit material brought from the zone of weathering. When they have access to open channels they penetrate deeper and deeper, absorb heat, and thus become powerful solvents of the metallic sulphides and tellurides.

The heating of the water circulation is, as stated, in part due to the secular rise of temperature in the earth's crust; but an even more important rôle in this respect is played by igneous intrusions. The occurrence of valuable ore deposits in the neighbourhood of igneous

<sup>1</sup> From the Latin *vadosus*, shallow; F. Posepny, *Trans. Amer. Inst. Min. Eng.*, 23. (1894), reprint, p. 17.

bodies has been frequently noted. A reasonable explanation of this phenomenon is that the heat furnished by the igneous rocks promotes the work of underground solutions. An igneous intrusion, therefore, may not only provide the material which goes to form an ore deposit, but also supply the heat necessary for its concentration.

The heated waters, whether of magmatic or of meteoric origin, ascend, and, as they cool and mingle with descending vadose waters, deposit their mineral burden, either in the main channels of circulation, where they form mineral veins, or in the pores of the rocks, which they thus tend to cement. With the closing of the openings, however, the circulation becomes feeble and ultimately completely stops, although earth movements may re-fracture the rocks and inaugurate a new circulation. The vertical movement of the water is confined to the zone of fracture and cementation. Below this zone the pressure is sufficiently great to produce a differential movement of the rock particles and thus to close all openings by rock flow.

For a free upward movement of the water the ground must be fissured, fault fractures and shear zones being preferentially used, and these therefore frequently become the seat of the deposition of ores (*see* p. 98). The existence of impervious formations is an important factor in directing the general circulation of underground waters and in localizing ore deposits.

The deposition of minerals from solution is brought about in a variety of ways. Solutions which are unsaturated at depth become, as they ascend, saturated by decrease of temperature and pressure. Compared to change of temperature the effect of pressure on solution is comparatively unimportant, unless gases are present, when a fall in pressure may have an important effect. Chemical reactions also come into play, for instance, between solutions of different origin, between

solutions and solids (for instance, in the wall rocks) and between solutions and gases. Under one or more of these conditions the metallic burden is precipitated, lining and ultimately filling the channels traversed by the solutions.

The growth of mineral deposits is in all cases probably very slow, and a continuous deposition from true molecular solutions is not possible without the continuous addition of the precipitating agent. An important rôle is probably played by colloidal solutions in which solids are dispersed in a very fine state of subdivision. The concentric and banded structures of certain mineral deposits such as malachite (a hydrated carbonate of copper) and wood-tin (an amorphous dioxide of tin distinct from cassiterite) are more easily explained by separation from a colloidal system than from molecular solutions.

The ore channels are of great diversity. The openings may be those of discission, i.e. fractures of dislocation (faults), or contraction joints; they may be due to the folding of sedimentary beds (saddles); or they may be those of solution in limestone and dolomite, e.g. caves, sink-holes, and enlarged joints and bedding planes. The filling of fault-fissures and zones of brecciation gives rise to important vein-deposits. Examples are to be found in the tin and lead-zinc lodes of Great Britain (*see* Fig. 10), the gold-bearing veins of the great Mother Lode zone of California, the Kolar gold lodes in Southern India, the gold-telluride lodes of Kalgoorlie in Western Australia, the Obuasi gold reef of the Ashanti goldfield, the silver-tin veins of Potosi, Bolivia, and the silver veins of Cobalt, Ontario. The latter are of especial interest. The silver-bearing veins occur in the lowest division of the Huronian and in the unconformably underlying Keewatin formation. They are remarkably

narrow, the great majority of the veins appearing as the filling of fault-fissures often only a fraction of an inch in width. Many are from one to two inches in width, and eight inches is about the maximum. The pay portions of the veins are generally limited to a few

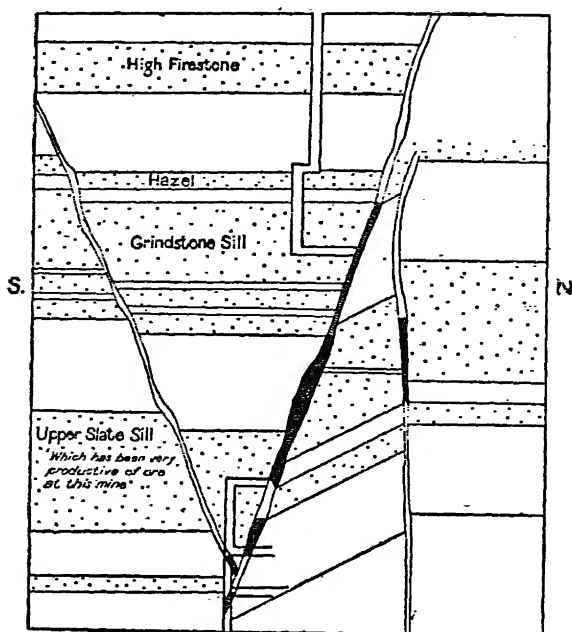


FIG. 10.—Section of Sharnberry mine, Teesdale, showing lead-zinc ore filling fault fracture in Millstone Grit beds.—From *Special Rep. Geol. Surv. of Great Britain*, 26. (1923), p. 17.

hundred feet along the strike, but as veins of barren calcite they extend to great distances. In depth, the very rich ore, which carries from 2,000 to 6,000 ounces of silver per ton, occurs in shoots which, as a rule, are not more than 200 feet in length. The silver is largely native, but the sulphides—pyrargyrite, proustite, argentite, and tetrahedrite also occur. Common associates of the silver minerals are the arsenides of cobalt and



nickel—smaltite ( $\text{CoAs}_2$ ), chloanthite ( $\text{NiAs}_2$ ), cobaltite ( $\text{CoAsS}$ ), and niccolite ( $\text{NiAs}$ ). Nickel sulphide, millerite ( $\text{NiS}$ ) and arsenical pyrites ( $\text{FeAsS}$ ) also occur. The presence of cobalt is indicated at the outcrop by the delicate pale-red colour of cobalt bloom (erythrite),

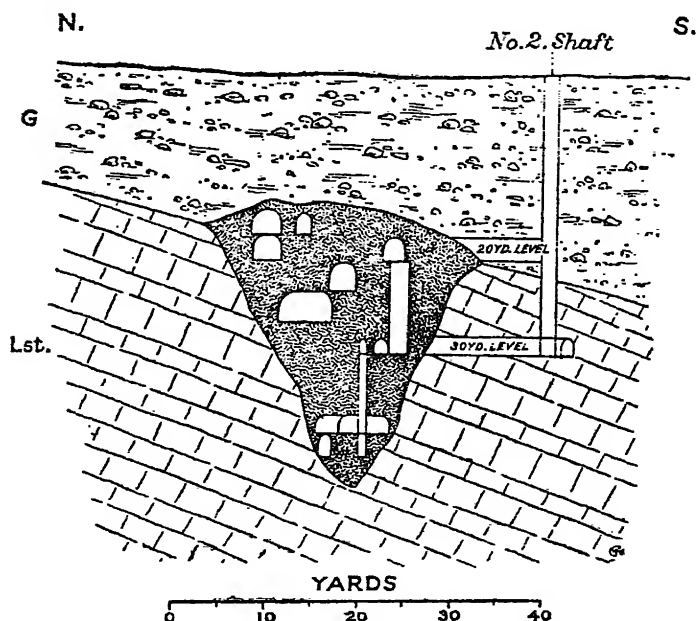


FIG. 11.—Cross-section of Green Haume mine, Dalton-in-Furness, showing hæmatite filling swallow-hole in Carboniferous limestone—a so-called "sop." G, Glacial beds; Lst., Limestone.—From *Special Rep. Geol. Surv. of Great Britain*, 7. (1924), p. 193.

the hydrous arsenate of cobalt. Calcite with a little quartz are the usual gangue minerals.

The filling of cavities at the apex of anticlinal folds with auriferous quartz (saddle-reefs) is a feature of the Bendigo Goldfield in Victoria, Australia. Further reference to these saddle-reefs is made on p. 106.

Solution cavities in limestone are often the receptacles for the deposition of minerals, especially lead and

zinc-ores, e.g. the famous deposits of the Mississippi Valley (Joplin), and of iron-ores, e.g. a few of the hæmatite deposits in Cumberland and Lancashire ("sops"). In Malaya tin-bearing clays are found filling solution cavities in the Kinta limestone. Originally they were part of the schist series overlying the limestone. Subterranean hollows formed by the dissolution of the

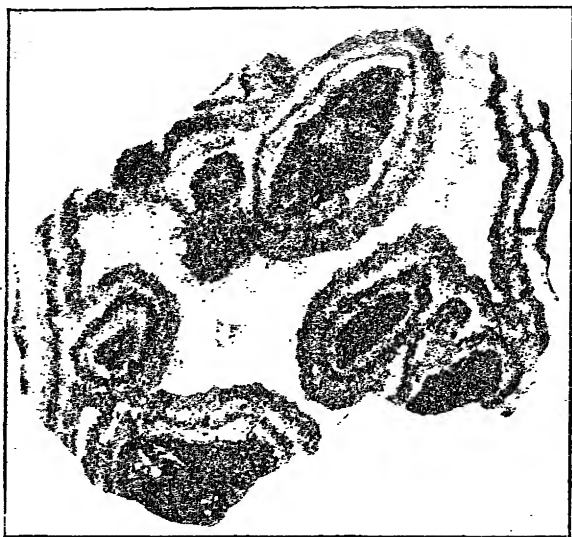


FIG. 12.—Photograph showing successive banding (crustification) around rock fragments in vein deposit at the Alacran mine, Zacualpan, Mexico. Width of specimen, 6 inches.—After Spurr. *Econ. Geol.*, 21. (1926), p. 520.

limestone increased in size until the overlying formation collapsed into them, forming a brecciated and dis-integrated mass suitable for excavation by hydraulic methods.

Not only are open channels filled: the wall-rocks of the fissures may be affected or the constituent minerals of the country rock attacked by the penetration of the circulating waters. The formation of new minerals by





reactions between the original constituents of a rock and solutions coming from some external source is termed *metasomatism*. Such alterations can be effected not only by water below the critical temperature, as in the hydrothermal circulation, but also by highly heated gases, as in pneumatolysis.

Cavity-filling is usually distinguished from metasomatic alteration by the deposition of the different

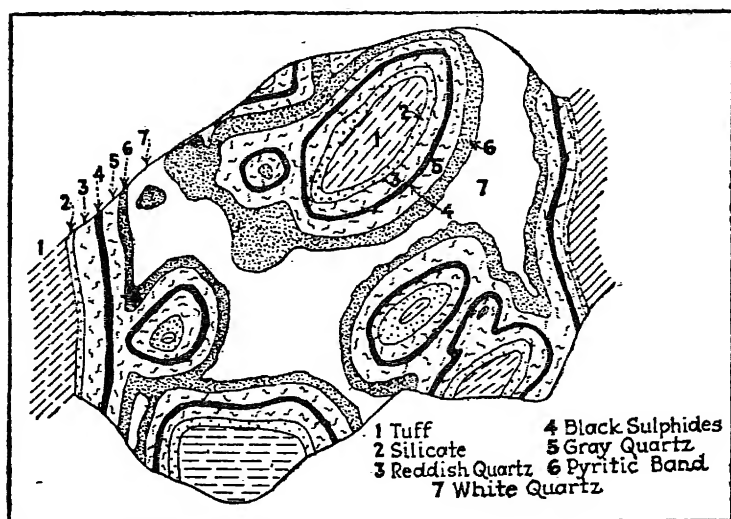


FIG. 13.—Key to Fig. 12.

minerals in successive layers. The whole cavity may be filled, or a central druse left open. Should the cavity contain foreign bodies, as in the case of a brecciated fracture, these will be found coated with the same succession of mineral layers that line the walls, thus forming *crusted kernels*. The absence of *crustification*, however, cannot be taken as evidence that an ore body has been formed by metasomatism, because in some cases cavity-fillings show no crustification. Other criteria, therefore, must be applied. Metasomatic ore

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bodies for the most part have either no defined walls or at most only one, whereas veins formed by cavity filling always have two walls. Unsupported residual nuclei of the original rock are characteristic of replacement ore bodies, and such isolated pieces of the country often conform in stratification with the country outside the cavity. Again, any structural peculiarities that characterize the replaced rock are reproduced in the replacing mineral. Thus the cellular structure of the Rauchwacke of Northern Germany is reproduced in the calamine that replaces it; the bivalves and molluscs of the Bleiberg limestones of Carinthia are reproduced in galena and calamine; the brachiopods characteristic of Silurian limestone are found in the iron-ores of Central Bohemia. Other structures frequently preserved in the altered rocks are those of stratification, shearing, joints and faults, brecciation, and the phenocrysts of igneous rocks.

Since different minerals are differently affected by solutions, rocks will be more or less completely replaced according as they are made up of aggregates of the same or of different minerals. Limestones and dolomitic limestone, which are composed almost entirely of either calcite or dolomite, are far more extensively and completely replaced than any other type of rock. They lend themselves to replacement both by the facilities they offer for circulation and by the solubility of the carbonates of which they are composed.

Where rocks of differing susceptibility to replacement occur in alternate beds the more soluble will be preferentially replaced, thus giving rise to a bedded type of ore deposit.

Impervious beds crossing the paths of vertical fissures retard or stop the flow of solutions, with the result that the latter, in spreading out beneath or above the impervious layer, tend to form characteristic pear-shaped

replacements (*see* Fig. 14). In cases where there is a rapid alternation of impervious and permeable layers selective action leads to the formation of serrated or tooth-shaped ore bodies.

In sandstones with a calcareous cement the replacement of the calcite by ores is common, but it is sometimes difficult to say whether the disseminated ore particles have been produced by replacement or by

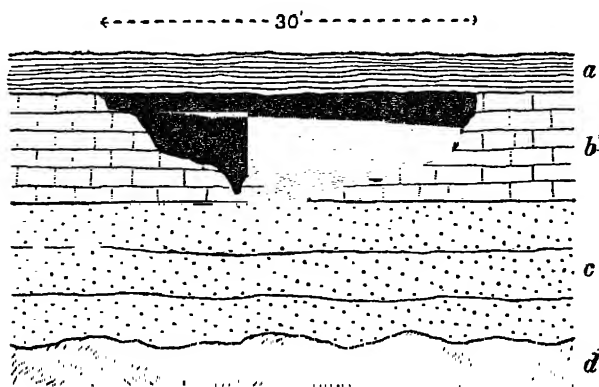


FIG. 14.—Pear-shaped replacement at the Union mine, Black Hills, U.S.A. : *a*, clay slate ; *b*, dolomite and ore ; *c*, quartzite ; *d*, schist.—After J. D. Irving.

the filling of inter-granular spaces. Sandstones with disseminated copper ore are of frequent occurrence ; those of Alderley Edge in Cheshire may be quoted as an example. Sandstones with disseminated galena occur at Commern and Mechernich in Rhenish Prussia.

Disseminated ore bodies may also be produced by the differential alteration of igneous rocks, since these are aggregates of minerals differing in susceptibility to alteration. A number of pyritic deposits, which derive their value from the presence of a small percentage of chalcopyrite and minute quantities of gold and silver, are normal hydrothermal replacements, in most cases

of shear-zones in the neighbourhood of intrusions. Their origin is spoken of as magmatic by some authors because the solutions carrying the ore material no doubt emanated from the magma reservoir that yielded the intrusions. The Huelva district of Southern Spain has typical examples of such deposits. Thus Bateman<sup>1</sup> describes the ore deposits of Rio Tinto as normal hydrothermal replacements by solutions which, arising

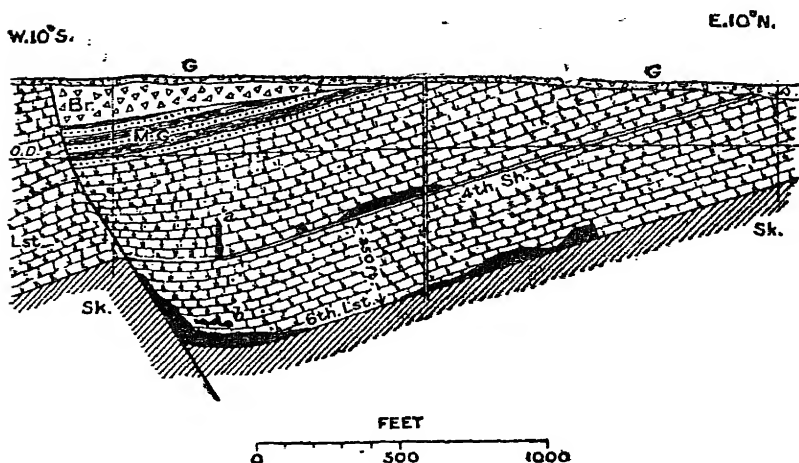


FIG. 15.—Section across Moss Bay mine, Cumberland, showing flats and pitches of hæmatite ore in Carboniferous limestone: G., Glacial beds; Br., Brockram; Lst., Limestone; Sh., Shale; Sk., Skiddaw Slate.—From *Special Rep. Geol. Surv. of Gt. Britain*, 7. (1924), p. 100.

from the magma reservoir that yielded the intrusives, followed shear-zones and replaced the adjacent porphyry and slates with sulphides. The microscopic evidence is conclusive: the banded ore is not due to post-ore shearing, nor to original flow—it is a structure inherited from the original sheared rock replaced by sulphide. The aureole of sericitic alteration which flanks the ore is characteristic of the work of hot waters. A more detailed description of the Rio Tinto deposit, with

<sup>1</sup> A. M. Bateman, *Econ. Geol.*, 22. (1927), p. 613.

special reference to its secondary enrichment, is given on p. 68. Other examples are Mount Lyell in Tasmania, Rammelsberg in Germany, Besshi in Japan, Tyee on Vancouver Island and Shasta in California.

Many lead-zinc deposits are metasomatic replacements, especially when they occur in limestone. Those of Derbyshire, North Wales (Halkyn Range), and the North of England (Pennine Range and Weardale) are examples. Although not in direct genetic connection with known igneous intrusions, they appear from the paragenesis of their mineral content to have a deep-seated magmatic origin. The presence of considerable

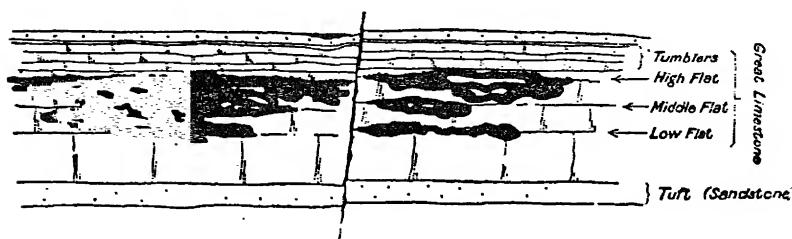


FIG. 16.—Section of "flats" of lead-zinc ore in the Boltsburn mine, Weardale, Cumberland (scale 80 ft. to 1 inch).—From *Spec. Rep. Geol. Surv. Great Britain*, 26. (1923), p. 10.

quantities of fluorspar, especially in Derbyshire and Weardale, is significant. These replacement deposits occur in Lower Carboniferous limestone. They are selective, the particular bed known as the "Great Limestone," some 65 feet thick, being especially favoured. Two types of replacement are common, viz. *flats* and *pitches*. A flat is a chamber-like replacement which has progressed outwards into the limestone from bedding planes. On the other hand, a pitch is a replacement which has proceeded from joints in the limestone. The names refer, of course, to the horizontality, on the one hand, and to the steep dip, on the other hand, of the respective deposits.



Lead-zinc replacements of limestone or of sheared zones in other rocks occur in the Cordilleran region of the United States and Mexico, Colorado (Leadville), Nevada, Utah (Tintic and Park City), Mexico; in Burma (Bawdwin), New South Wales (Broken Hill); and many other places.

The so-called *blanket* deposits (mainly lead-zinc ores) of Leadville are particularly instructive. Here the ore-bearing solutions have reacted with the limestones of the district where their upward course was checked by sheets of intrusive porphyry. It is generally believed that these solutions were derived from the same magma as the porphyries but at a later stage of differentiation. S. F. Emmons, in discussing in his classic Memoir<sup>1</sup> the origin of the Leadville deposits, says: "In the great sulphide bodies of these mines not only could every detail of the granular structure, joints and cleavage of the original limestone be detected at times in the sulphide ore, but even the cracks on the top. In abandoned drifts where limestone dust had accumulated on the walls one would have supposed them to be of limestone until the breaking off of a fresh fragment by the hammer showed the metallic gleam beneath." Where fossils were present in the original limestone, these are also replaced by the ore, their form being preserved.

Another instructive example of metasomatic replacement is furnished by the hæmatite deposits of the North-West Coast of England (Cumberland and Lancashire). The ore bodies occur as irregular masses in Carboniferous limestone and are generally connected with fault fractures or impervious beds. The largest ore bodies are those worked by the Florence and Ullcoats mine near Egremont and the Hodbarrow

<sup>1</sup> "The Geology and Mining Industry of Leadville," *U.S. Geol. Survey, Mem.* 12. (1886). Cf. Prof. Paper 148 (1928).

mine in the Millom district, both in the county of Cumberland. The limestone rests on an impervious floor of Ordovician and Silurian slates, and is overlaid unconformably by Permian and Triassic strata. Much iron is present as a cementing material of the sandstones and conglomerates of these upper measures, and the hæmatite iron-ore that replaces the limestone is generally accepted as having been derived from the beds overlying the limestone, from which the iron has been carried by descending solutions. The metasomatic character of the ore bodies is indicated by the presence in the heart of the ore bodies of scalenohedral crystals of calcite and brachiopod shells and crinoids completely altered to hæmatite, and by the fact that the original bedding planes of the limestones are frequently discernible in the ore bodies.





## CHAPTER VII

### THE ALTERATION OF ORE DEPOSITS

It was shown on page 49 that the free circulation in the zone of percolation of waters charged with oxygen and carbon dioxide makes it, in effect, one of oxidation, in which rocks and ore deposits become disintegrated, and their component minerals decomposed, with removal of the soluble constituents. The chief chemical processes involved are hydration, oxidation and carbonation. Silicates are broken down, the alkalies and alkaline earths being removed as soluble bicarbonates, whilst silica is set free. Sulphides give place to soluble sulphates or to sulphuric acid. Iron, aluminium and manganese compounds yield their respective hydrates (limonite, bauxite, and wad or psilomelane); hydrated silicates of aluminium and magnesium are formed (kaolin, lithomarge, talc, chlorite, etc.), as also the sulphates of calcium and barium (gypsum and barytes). Comparatively few minerals completely resist prolonged action of the destructive agents. Quartz and other forms of silica, on account of their ubiquitous occurrence, are the most important. Equally indestructible are the oxides (magnetite, ilmenite, chromite, cassiterite, rutile, zircon, spinel and corundum), the metals (platinum and gold) and the diamond. The silicates are only partially resistant, e.g. the feldspars, mica, hornblende, tourmaline, axinite, andalusite, kyanite, topaz and garnet.



These materials are for the most part transported mechanically. Some of them remain behind as residual deposits. The soluble compounds are carried down to the belt of saturation. A portion is lost in the waters escaping in the zone of discharge; the remainder is deposited as the descending acid waters become neutralized by the alkaline waters of the lower zone. When the rocks contain iron in any considerable

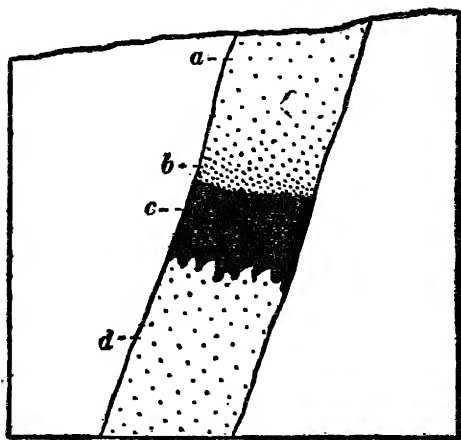


FIG. 17.—Diagrammatic section of an enriched copper lode: *a*, leached zone; *b*, rich oxidized zone; *c*, rich sulphide zone; *d*, lean sulphide ore.—After W. H. Emmons. *Gen. Econ. Geol.*

quantity, the belt of saturation is often clearly marked off by a difference in colour from the oxidation zone, the formations within the latter being stained red or yellow by the hydrated oxide of that metal, while the unoxidized rocks have a bluish or greenish hue due to the prevalence of iron sulphides and ferrosilicates.

The changes produced in ore deposits by the process described above are most striking and of the greatest economic importance. Those metals that form

soluble compounds are removed from the zone of weathering, leaving in most cases an impoverished residual material. On the other hand, the precipitation at lower levels of new metallic compounds, or of the metals themselves, leads to an enrichment of the deposit at those levels. As a rule, oxy-salts, halogen salts and native metals are precipitated above the water-table, while secondary sulphides are deposited below it (*see* p. 48).

The dictum of the mining camp that lodes become richer in depth is therefore only true as regards their upper portions. In progressing from the outcrop downwards, a barren or lean portion of the lode is first passed through. As the water-table is approached, the metal content increases, attaining a maximum in a zone of secondary sulphides below it; the grade then falls until a minimum is reached in the unenriched zone of lean primary sulphides.

Under favourable conditions the enrichment is the greater the longer the lode has been under the influence of weathering. In other words, the concentration is directly proportional to the amount of erosion, since the progress of the latter is constantly bringing portions of the lodes, that have already been enriched, nearer the surface, with the result that increasingly richer material is carried down to the zone of precipitation. There is consequently no limit to the amount of enrichment that may take place, provided the favourable conditions are maintained.<sup>1</sup>

On the other hand, in countries like Canada, that have been exposed to the erosion of recent glaciation, the lean sulphide ores often extend to the surface, or are found unaltered beneath a covering of glacial drift. In such cases all oxidation products and enriched portions of the lode have been pared away by the

<sup>1</sup> W. H. Emmons, *U.S. Geol. Surv., Bull.* 625. (1917).

erosion of the ice-sheets, and the subsequent lapse of time has not been sufficient to reproduce them.

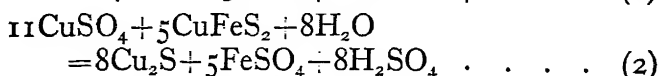
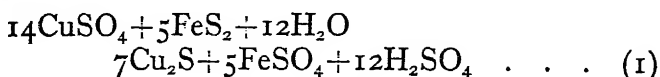
The zone of secondary enrichment is of prime importance for the mining of copper and silver. In the case of the former it is probably true that the bulk of the metal used in commerce is won from it. Copper-mines that are rich in their upper levels become poorer in depth and ultimately unpayable when the lean primary ores are reached, unless the deposits are sufficiently large to be worked at a low cost.

In the zone of primary sulphides copper is almost invariably associated with sulphides of iron; indeed, in many cases, as at Huelva (Rio Tinto), at Butte (Anaconda), and in the Morenci district of Arizona, the copper of the primary ores is present as a constituent of iron pyrites and not as recognizable chalcopyrite. On oxidation the copper goes into solution either as sulphate or as a bicarbonate, and is removed, leaving behind the iron oxides. Consequently a prominent feature in the case of copper lodes is the formation at or near the surface of what is known as "gossans" or iron-caps (*chapeaux de fer*), from which the valuable copper content has been removed. These in wet climates consist principally of hydrated oxides of iron. In drier climates, the anhydrous oxide (hæmatite) occurs; and in still drier climates (for instance, the rainless regions of Arizona and Chile) the gossans contain chlorides and sulphates of copper, which in wet climates are unable to exist in the solid state.

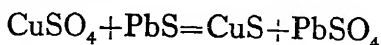
The copper minerals especially characteristic of the upper portion of the zone of secondary enrichment are the hydrated carbonates—malachite ( $\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ ) and chessylite ( $2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$ ), the hydrated silicate—chrysocolla ( $\text{SiO}_2 \cdot \text{CuO} \cdot 2\text{H}_2\text{O}$ ), and an oxychloride—atacamite ( $\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2$ ), together with native copper. Lower down the sulphides—

chalcocite ( $\text{Cu}_2\text{S}$ ), bornite ( $3\text{Cu}_2\text{S}.\text{Fe}_2\text{S}_3$ ) and covellite ( $\text{CuS}$ )—are found.

As an example of the reactions by which copper is transferred from the upper portion of the lodes to the precipitation zone, the formation of chalcocite may be given: the oxidation of iron pyrites produces ferric sulphate, and this reacting on chalcopyrite ( $\text{Cu}_2\text{S}.\text{Fe}_2\text{S}_3$ ) forms sulphate of copper. In the precipitation zone it is reduced both by iron pyrites and chalcopyrite to chalcocite ( $\text{Cu}_2\text{S}$ ) as shown by the following reactions:



Precipitation takes place in proportion to the relative insolubility of the sulphides of the metals in question. Investigations by Schürmann<sup>1</sup> in 1888 established a series in which the sulphide of a metal would be thrown down at the expense of the sulphide of any metal following it in the list. Schürmann's series is as follows: palladium, mercury, silver, copper, bismuth, cadmium, antimony, tin, lead, zinc, nickel, cobalt, ferrous iron, arsenic, thallium and manganese. It has already been seen that copper sulphide is precipitated by iron pyrites or by chalcopyrite. Another case which frequently occurs in nature and can be imitated in the laboratory is the precipitation of copper sulphide by lead sulphide (galena),



Gold, too, which is dissolved as a chloride by ferric chloride in the presence of manganese, is easily reduced again by metals or their sulphides or by carbon.

<sup>1</sup> E. Schürmann, *Liebig's Annalen*, 249. (1888), p. 326.

The minerals characteristic of the enriched zone of ore deposits are very diverse and complex. As shown above, they are products of oxidation above the water-table and secondary sulphides below it. The primary minerals from which they are originally derived are

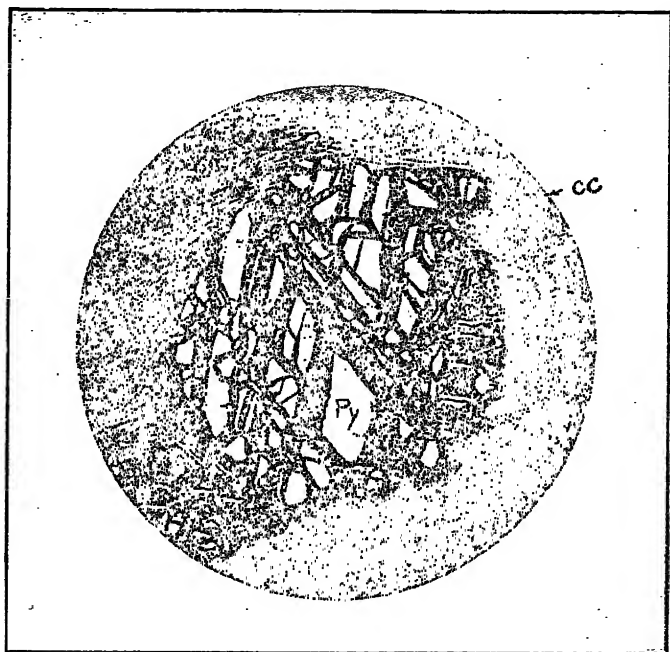


FIG. 18.—Photo-micrograph ( $\times 290$ ) illustrating the enrichment of copper-ore, chalcocite replacing pyrites, Magma mine, Arizona.—After Short and Ertlinger. *Trans. Amer. Inst. Min. Met. Eng.*, 74 (1926), p. 123.

as follows: **iron**—pyrites ( $\text{FeS}_2$ ), pyrrhotite ( $\text{FeS}$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), and the ferro-magnesian silicates occurring in igneous rocks; **manganese**—the manganese silicates of the igneous rocks, such as rhodonite, tephroite and spessartite; **nickel**—nickeliferous pyrrhotite ( $\text{FeS}$ ) and its isomorph pentlandite ( $\text{Fe,NiS}$ ); **copper**—chalcopyrite ( $\text{Cu}_2\text{S} \cdot \text{Fe}_2\text{S}_3$ ), bornite ( $\text{Cu}_3\text{FeS}_3$ ),

and cupriferous iron pyrites in which copper is usually present in extremely small quantities; **lead** and **silver**—galena ( $\text{PbS}$ ) and argentiferous galena, which probably contains the isomorphous argentite ( $\text{Ag}_2\text{S}$ ); **zinc**—zinc-blende ( $\text{ZnS}$ ); **antimony**—stibnite ( $\text{Sb}_2\text{S}_3$ ); **arsenic**—mispickel ( $\text{FeAsS}$ ).

The table on pages 70 and 71 shows the chief oxidation and reduction products of the primary minerals.

The special list of silver sulphides, etc., referred to therein is the following:

Name	Percentage of Ag	Chemical Formula	Crystallographic System
Argentite . . . . .	87	$\text{Ag}_2\text{S}$	Cubic
Argentiferous galena . . . . .	—	$(\text{Pb}, \text{Ag})_2\text{S}$	Cubic
Acanthite . . . . .	87	$\text{Ag}_2\text{S}$	Orthorhombic
Stromeyerite . . . . .	3-60	$(\text{Cu}, \text{Ag})_2\text{S}$	Orthorhombic
Polybasite . . . . .	62-75	$9(\text{Ag}, \text{Cu})_2\text{S} \cdot \text{Sb}_2\text{S}_3$	Monoclinic
Pearcëite . . . . .	55-78	$9(\text{Ag}, \text{Cu})_2\text{S} \cdot \text{As}_2\text{S}_3$	Monoclinic
Stephanite . . . . .	68	$5\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$	Orthorhombic
Pyrargyrite . . . . .	60	$3\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$	Hexag.-rhombohedral
Proustite . . . . .	65	$3\text{Ag}_2\text{S} \cdot \text{As}_2\text{S}_3$	Hexag.-rhombohedral
Tetrahedrite . . . . .	0-30	$3(\text{Cu}, \text{Ag})_2\text{S} \cdot \text{Sb}_2\text{S}_3$	Cubic
Miargyrite . . . . .	—	$\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$	—
Freieslebenite . . . . .	0-23	$5(\text{Pb}, \text{Ag})_2\text{S} \cdot 2\text{Sb}_2\text{S}_3$	Monoclinic

\* Isomorphous.

An instructive example of secondary enrichment is afforded by the great copper-mining district of Huelva in Southern Spain and Portugal, of which the Rio Tinto mine is the most prominent representative. The copper belt, from which, it is computed, the Romans mined 30 million tons of ore, is situated at the southern end of the Iberian Meseta—a fractured tableland of Palæozoic sedimentation but Permo-Carboniferous tectonic structure. It is one of the old Hercynian fragments, like Cornwall and Devon, Brit-

tany, the Central Plateau of France, the Vosges, and the Harz—all well-known mining districts.

The folding on east and west lines was accompanied by the intrusion of granite, porphyry and, at a later stage, basic sills and dykes, and by the deposition of ores such as the cupriferous pyrites deposits of Huelva, the mercury-ores of Almaden, and the lead-zinc ores of Central Spain (Linares and Ciudad Real).

The Huelva deposits, consisting mainly of iron pyrites with a small percentage of copper present as finely disseminated chalcopyrite, occur as lenses, or lenticular lodes, in shear-zones in the porphyry, or at the contact of the porphyry with the Lower Carboniferous slates. The majority of the lodes vary in length from 1,000 to 2,000 feet, but in exceptional cases they reach as much as 3,000 or 4,000 feet. The maximum width is proportional to the length: in the majority of the larger lodes it ranges from 150 to 500 feet. The San Dionisio, probably the largest lode at Rio Tinto, reaches a width of 800 feet. The smaller lodes are from 50 to 100 feet. As a rule, the lodes feather-out along both strike and dip. After reaching a maximum, the length and width decrease at each successive level, and the ore body tapers gradually to a point, although occasionally, when the ore body rests on porphyry, its base is flat or rounded. It is probable that the vertical range of ore deposition in no case exceeded 3,000 feet, and as a result of denudation few lodes now attain to 1,000 feet. That the factor of denudation has been the all-important cause in determining the present vertical extent of the lodes is strikingly seen where two or more parallel lodes occur *en échelon*; in such cases, one lode will feather-out at a short distance below its outcrop, while its neighbour may be a considerable lenticle, which dies out before reaching the surface. As an extreme result of denudation, the root of an

Metals	Primary Minerals	Oxidation Products	
		Oxides and Hydrates	Carbonates
COPPER .....	Chalcopyrite $\text{Cu}_2\text{S} \cdot \text{Fe}_2\text{S}_3$ and Cupriferous Pyrites	Cuprite $\text{Cu}_2\text{O}$ Melaconite $\text{CuO}$	Malachite $\text{CuCO}_3 \cdot \text{Cu(OH)}_2$ Chessylite $2\text{CuCO}_3 \cdot \text{Cu(OH)}_2$
LEAD AND SILVER	Enargite $3\text{Cu}_2\text{S} \cdot \text{As}_2\text{S}_5$ Galena $\text{PbS}$ Argentite $\text{Ag}_2\text{S}$ Native Silver	Minium $\text{Pb}_3\text{O}_4$	Cerussite $\text{PbCO}_3$
ZINC .....	Zinc-blende $\text{ZnS}$	Zincite $\text{ZnO}$	Calamine $\text{ZnCO}_3$
GOLD .....	Auriferous Pyrites Native Gold Gold Tellurides	—	—
IRON .....	Pyrites $\text{FeS}_2$ Pyrrhotite $\text{FeS}$ Magnetite $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ Hæmatite $\text{Fe}_2\text{O}_3$ and Ferro-mag- nesian silicates	Limonite $\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$	Chalybite or Siderite $\text{FeCO}_3$
MANGANESE ....	Manganese-bear- ing silicates	Pyrolusite $\text{MnO}_2$ Psilomelane Wad	Rhodochrosite $\text{MnCO}_3$
NICKEL .....	Nickeliferous Pyrrhotite Pentlandite $(\text{FeNi})\text{S}$	Annabergite (nickel-bloom) $3\text{NiO} \cdot \text{As}_2\text{O}_5 \cdot 8\text{H}_2\text{O}$	Zaratite (Emerald nickel) $\text{CO}_2 \cdot 3\text{NiO}_2 \cdot 6\text{H}_2\text{O}$



Oxidation Products			Reduction Products
Sulphates	Chlorides and Phosphates	Silicates	
Chalcanthite $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	Atacamite $\text{CuCl}_2$ $+ 3\text{Cu}(\text{OH})_2$	Chrysocolla $\text{CuO} \cdot \text{SiO}_2$ $+ 2\text{H}_2\text{O}$	Native Copper Tetrahedrite Chalcocite $\text{Cu}_2\text{S}$ Bornite $3\text{Cu}_2\text{S} \cdot \text{Fe}_2\text{S}_3$ Covellite ( $\text{CuS}$ )
Anglesite $\text{PbSO}_4$	Pyromorphite $3\text{Pb}_3(\text{PO}_4)_2$ $\text{PbCl}_2$ Kerargyrite $\text{AgCl}$ Embolite $\text{Ag}(\text{ClBr})$ Matlockite $\text{PbCl}_2 \cdot \text{PbO}$ Mendipite $\text{PbCl}_2 \cdot 2\text{PbO}$	—	Complex Sulphides and Arsenides of Silver (see special list) Native Silver
—	—	Willemite $\text{SiO}_2 \cdot 2\text{ZnO}$ Hemimorphite $\text{SiO}_2 \cdot 2\text{ZnO} \cdot \text{H}_2\text{O}$	—
—	—	—	Native Gold
Copperas or Melanterite $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	Vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	—	—
—	—	Braunite $\text{Mn}_2\text{O}_3$ $+ \text{MnSiO}_3$	—
—	—	Garnierite (hyd. sil. of Ni and Mg)	Millerite $\text{NiS}$ Niccolite $\text{NiAs}$ Gersdorffite $\text{NiAsS}$ Chloanthite $\text{NiAs}_2$

eroded lode may be found completely converted into gossan with no underlying sulphide ore.

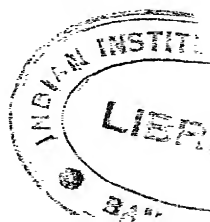
The gossan of the oxidized zone is a massive hæmatite containing over 50 per cent. of iron and no copper. Its lower limit (about 100 feet below the surface) is sharp and well defined, and is determined



FIG. 19.—Photo-micrograph of polished specimen of Rio Tinto ore showing enrichment by covellite (Cv) replacing chalcopyrite (Cp).—After A. M. Bateman, *Econ. Geol.*, 22. (1927), p. 599.

by the topographic level of the ground-water. It is sometimes marked by an earthy layer carrying considerable values in gold and silver, the latter being present largely as the chloride (cerargyrite) in association with the sulphate of lead (anglesite). They were doubtless carried there from the overlying zone in solution in ferric sulphate.

Next follows a zone of secondary copper enrichment.



It has a vertical range of about 150 feet, but owing to its gradual transition to the lean primary ore its depth cannot be stated very exactly. This enriched ore assays from 3 to 12 per cent. copper. It carries chalcopyrite, chalcocite and covellite as the chief products of enrichment, these minerals being abundant

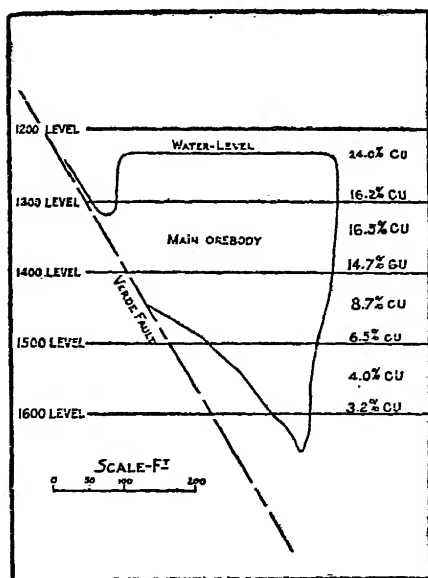


FIG. 20.—Cross-section of ore body, United Verde Extension mine, Arizona, showing decreasing enrichment below the permanent water-level.—After J. L. Fearing, *Econ. Geol.*, 21. (1926), p. 269.

in the upper part of the zone as veins filling cracks both in the ore and in the adjoining country-rock. Bornite is not very characteristic, but tetrahedrite and other silver-bearing sulphides are in places abundant.

The copper content of the bulk of the underlying lean primary ore, in the main iron pyrites, varies from 0.8 to 2 per cent., and in some cases only averages 0.5 per cent.



Finlayson<sup>1</sup> regards the formation of the lodes as due to the metasomatic replacement of crushed rock in sheeted zones between planes of faulting and thrusting, the ore minerals being introduced by ascending thermal solutions; further, he assumes that a certain amount of concentration by magmatic differentiation must have taken place in a deep-seated igneous magma before the thermal waters came into action (*see* p. 58).

It is the secondary enrichment which has given this field its economic importance as a source of copper. Without secondary enrichment, the primary ores would be of too low a grade for profitable working.

Instances of the secondary enrichment of copper ores might be multiplied indefinitely. Writing in 1891 on the Butte copper mines, James Douglas pointed out that the leaching of the upper 400 feet of the lodes in the oxidized zone had produced in the underlying ore a zone 200 feet deep in which the normal copper content is doubled. The primary ores consist of pyrites and enargite, together with a little chalcopryrite. The secondary ores are chalcocite and subordinate covellite. The barren zone consists mainly of honeycombed quartz. In Arizona there are numerous examples (Clifton, Globe, Ray, Bisbee) of enrichment by the replacement of pyrites by chalcocite: the result in general is the formation of a chalcocite zone some hundreds of feet in thickness, containing from 2 to 4 per cent. of copper. This is overlaid by a leached zone containing some oxidized copper ore and is underlaid by a lean cupriferous pyrites deposit. At Bisbee the oxidized zone is of considerable depth and contains copper carbonates and cuprite.

An exceptional case of enrichment is that of gold-quartz veins which have been subjected to differential leaching in the zone of weathering. It is based on the

<sup>1</sup> A. M. Finlayson, *Econ. Geol.*, 5. (1910), pp. 357-372, 403-437.

reduction of volume brought about by the removal of the sulphides of iron, with consequent increase in the ratio of gold to vein material. An example of this is furnished by the Mount Morgan mine in Queensland, Australia. This mine was long famous as one of the great gold-producers of the world. Up to the end of 1907, 3 million tons of ore from the oxidized zone had been treated, yielding  $13\frac{1}{2}$  million pounds, mostly as gold, of which 7 million pounds sterling was paid in dividends. The mine, down to the 450-foot level, consisted of a huge open working with benches of from about 60 to 70 feet, the area of the open working covering about 14 acres. Below the 450-foot level, the ore was mined underground, stoping being by the square-set system.

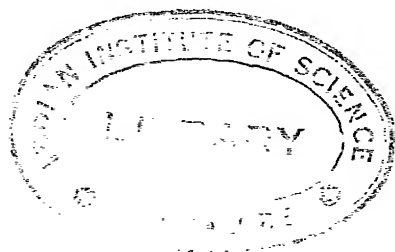
The country-rock consists of sediments (the so-called Gympie series) of Carboniferous age. In these alternating quartzites and slates, inclined at an angle of about 20 degrees, are intercalated quartz-porphyrries, which may be lavas or possibly intrusive sills. An intrusion of basic dykes has shattered this formation, and the shattered area has been permeated by mineral-bearing solutions coming from below, with deposition of silica, iron pyrites, chalcopyrite and a small amount of gold, the process being one of metasomatic replacement.

Subsequently the upper part of the deposit was completely oxidized, the sulphide being destroyed with removal of both iron and copper. A residual cellular or sintery quartz mixed with kaolin resulted from the action of sulphuric acid on the felspar of the igneous dykes; a further product being gypsum from the lime liberated by the destruction of the felspar. The removal of so much material of high density increased the ratio of gold to vein-stuff very considerably. Hence in its upper oxidized portion the Mount Morgan was a gold-

mine, copper production being of trifling importance. Such copper as occurred consisted of small quantities of the oxidized ores, such as cuprite, malachite, chersylite, chrysocolla and chalcantite.

The change from completely oxidized ore to pyritic ore takes place at varying levels in the open cut. It begins at about 250 feet below the summit, while the main body of pyritic ore is reached at about 316 feet. In the upper part of the sulphide zone, the pyrites is much mixed with oxides of iron of secondary origin, resulting from the decomposition of the chalcopyrite of the original ore. Below this partially leached zone occur the unaltered sulphides, in which the copper amounts to about  $3\frac{1}{4}$  per cent. and the gold to 5 dwts. to the ton.

As in the progress of the mining operations the rich gold ores of the oxidized zone became exhausted and the pyritic ores more heavily drawn upon, the production of gold fell off, while the copper production increased, so that we have here an example of the change from a gold-mine in its upper levels to a copper-mine with subordinate gold production in its lower levels.



## CHAPTER VIII

### ORE FORMATION BY MECHANICAL AGENCIES

As shown in the previous chapter, the work of weathering is twofold; namely, mechanical disintegration and chemical change. Comparatively few minerals resist the prolonged attack of chemical agents; but amongst them there are some that are of importance from the economic point of view, e.g. gold, platinum, magnetite, chromite, cassiterite, monazite, corundum, diamond, etc. The agents of mechanical disintegration are the diurnal and other variations of temperature, the expansion of water on freezing, the erosion due to running water, the sand-blast action of wind, etc.

The detritus thus formed is carried down the slopes of the hills by running water and distributed according to specific gravity and size of grain. This transported material accumulates in the valleys of rivers, in lakes, or on sea-beaches, and the resulting gravel and sand deposits are accordingly classed as alluvial, lacustrine and marine, or littoral. A large proportion of the world's gold has in the past been won from them. On account of its high specific gravity the metal is concentrated in the coarse gravels and among the boulders at the bottom of the placers, the most valuable accumulations being often actually on the bed-rock itself. If the latter happens to consist of steeply dipping schists or slates, the up-turned edges of the latter act as natural *riffles* or bars to catch and retain the gold particles. Accumulation

also takes place on what are known as *false bottoms*, which are beds of clay or sand cemented by iron (*pan*), alternating with the beds of gravel.

Placer-gold is usually associated with a heavy black sand consisting of magnetite, ilmenite and hæmatite, together with chromite, topaz, zircon, spinel and other heavy resistant minerals (*see* p. 62, Chapter VII); but obviously the particular association is determined by the nature of the parent rock. The character of the gold is variable: it occurs in flat scales and flakes, in rounded particles, and as irregularly shaped grains and nuggets bearing evidence of much attrition. In size it ranges from the finest dust to nuggets weighing thousands of ounces. It is probable that these large nuggets have increased since they were first deposited. The fact that auriferous pyrites is found replacing the woody fibre of tree-stems in the alluvial drifts of Victoria and California clearly shows that under favourable conditions an enrichment through chemical action (that is, solution and recrystallization) can take place.

The richest gravels are formed by a re-sorting of earlier auriferous gravels, which are often found as terraces several hundred feet above the workable deposits.

Placers occur in the river systems of every part of the world; but the greatest amount of gold has been won from the Recent and Pleistocene gravels of California, Alaska, Australia and Siberia. The older gravels are often deeply buried under a thick cover (*over-burden*) of clay, soil, peat, and moss, which is sometimes permanently frozen, as in the tundras of Siberia and Alaska; while in Australia and California the ancient river systems are concealed by later flows of lava, their auriferous gravels being known as *deep leads*. Thus, the Loddon Valley gravels of Victoria,



Australia, lie beneath 400 feet of massive basalt flows; and the Hidden Treasure gravel channel in Placer County, California, is worked below a thousand-foot cover of andesitic lavas, tuffs and breccias. The buried placers of California have been raised to an elevation of 2,600 feet above sea-level along the western flanks of the Sierra Nevada, the present river-bed being 1,500 feet below the old channel.

Auriferous beach deposits, or marine placers, are formed on certain coasts where the conditions are favourable for the separation, by surf action, of the gold and heavy minerals from the sand and lighter stones. Such deposits occur in New Zealand, on the beaches of Oregon, Alaska (Nome and Cape Yagtag), Chile and Nova Scotia. Usually the gold occurs in a black sand consisting of magnetite, ilmenite, and hæmatite, but this mineral association is not constant. While in New Zealand the black sands are so rich in iron that it has been seriously proposed to work them for that metal, in the Cape Yagtag deposits the iron-ores are absent, their place being taken by garnet.

The auriferous conglomerates (locally termed "banket") of the Witwatersrand in the Transvaal, which, since their discovery in 1886, have produced so large a proportion of the world's gold, are considered by some to be ancient placers. Against this view and in favour of a secondary origin for the gold it may be urged that the metal shows no evidence of detrital origin, occurring as it does in crystalline particles and minute flakes in close association with pyrites. Moreover, the rest of the cement consists of crystalline quartz, which has evidently been introduced, like the pyrites, subsequently to the deposition of the gravels. The only unmistakably primary constituents besides the quartz pebbles are platinum, osmiridium, diamond, chromite and zircon, while the following minerals

occurring in the cement are of secondary origin: quartz, chlorite, chloritoid, pyrites, marcasite, pyrrhotite, galena and blende.

If it be conceded that the gold derived from the denudation of quartz veins in the schists and granite of the Primitive System was deposited simultaneously with the quartz pebbles of the gravels, it must, on the other hand, be admitted that the original alluvial gold has been completely dissolved and reprecipitated.

The Witwatersrand System consists of a series of alternating beds of shales, quartzites and conglomerates, some 20,000 feet thick, with an east and west strike and a dip to the south. These beds must have been laid down near the mouth of a large river, and under conditions of intermittent submergence that permitted the deltaic gravels to be covered by deep-water muds. The gold-bearing conglomerates occur approximately in the middle of the System and consist of three principal members, namely the Main Reef, the Main Reef Leader and the South Reef. All three are economically important in the centre of the Rand (near Johannesburg). In the West Rand, however, the Leader is absent; while in the extreme East Rand it is the sole representative of the series. The gold content is small, the average grade of all the mines working in 1926 being only  $6\frac{1}{2}$  dwts. to the ton.

Platinum is occasionally associated with gold in the residual and alluvial gravels of California, British Columbia, Brazil, Colombia, and Borneo.

Workable platinum placers are found on the River Iss and other rivers draining the eastern slopes of the Ural Mountains in the district of Nischne Tagilsk and Mount Solovief. In these deposits the platinum is associated with chromite and magnetite; and its origin has been traced to intrusive masses of peridotite in

which there has probably been a magmatic concentration of these minerals.

In districts where granite prevails the river gravels often contain cassiterite, and such stanniferous gravels form the source of the bulk of the tin production of the world. In common association with the cassiterite are tourmaline, topaz, axinite, garnet, wolfram, scheelite, limonite, magnetite and other heavy and indestructible

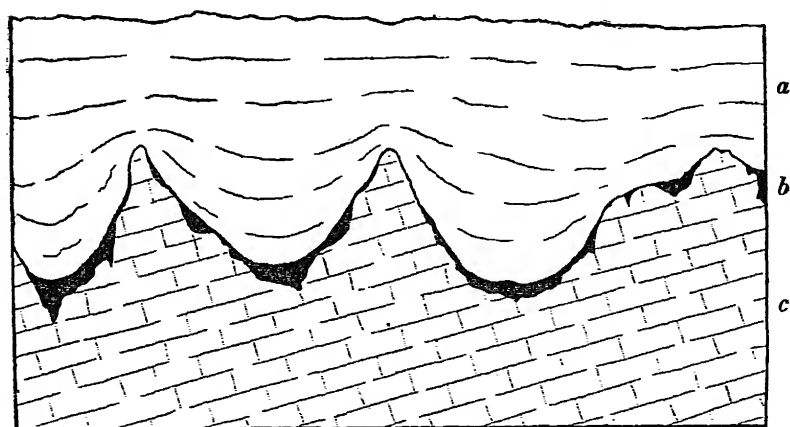
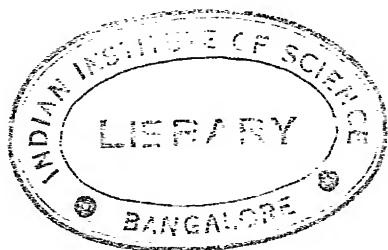


FIG. 21.—Diagrammatic section showing the occurrence of alluvial tin ore on an irregular limestone floor in Malaya: *a*, alluvium; *b*, payable tin ore; *c*, limestone. Note the limestone pinnacles.

minerals. As in the case of the gold placers, the concentrates accumulate at the base of the gravel on the bed-rock or floor on which the deposit rests. The gravels consist largely of tourmaliniferous quartz, greisen and “capel” derived from the tin-bearing vein-material of the granite rock, which by its denudation has given rise to the deposits. Stanniferous gravels occur in Cornwall, Malaya, Australia, Tasmania, Bolivia, Nigeria and in South Africa (Swaziland and the Transvaal).

Chromite gravels are formed by the disintegration

of chromite-bearing serpentine, as in New Caledonia. Iron-sands containing hæmatite, magnetite and ilmenite (e.g. those of Elba and New Zealand) and similar deposits of manganese ores are numerous. As a rule, they have weathered-out and undergone selective accumulation not far from the original source.



## CHAPTER IX

### RESIDUAL DEPOSITS

RESIDUAL deposits attain their greatest development in countries that have been unsubmerged for a vast period of time. In such countries, under favourable conditions of climate, such as the absence of glacial erosion, disintegration, accompanied by the removal of soluble material, may progress to many hundred feet below the surface. The whole of the solid rocks in this zone then are replaced by soft decomposition products that bear no likeness to their parent rock; although certain original structures, such as bedding and foliation, may be retained. Deep weathering of this nature may be well seen, for instance, in Brazil, in India, in Malaya and in Africa.

The materials composing the bulk of these deposits are gravel, quartz-sand and clay, or lithomarge (an amorphous hydrated aluminium silicate, having the composition of kaolinite, viz.  $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ ); and more exceptionally the mixture of hydrated oxides known as laterite. This latter material occurs in tropical and semi-tropical countries such as India, the Malay Peninsula, the Dutch East Indies, South America and East, West and South Africa; in fact, it appears to be one of the commonest residual products of ferruginous and aluminous rocks under suitable climatic conditions.

A great number of analyses of laterite have clearly established the fact that it consists to a large extent of

a mixture of oxides and hydrated oxides of iron, aluminium, titanium and manganese. They show that the water is chiefly combined with the aluminium oxide, the iron oxide being mostly present in the anhydrous or slightly hydrated condition (hæmatite or turgite).

The chief aluminium oxide present is gibbsite ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ), but diaspore ( $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) is also present in small proportions. The ratio between the iron oxides and the aluminium oxides may vary to any extent, so that while some laterites approximate in composition to high-grade iron-ores, others are almost pure bauxite.

In colour laterite is dominantly red or brown. It is, however, often mottled or streaky, and frequently contains whitish patches of a soft aluminous material from which the iron oxide has been withdrawn by segregation. Local concentration produces nodular concretions of iron oxides, and similarly manganese, when present, is concentrated in nests or black botryoidal aggregates of the various oxides of that metal.

Most laterites are traversed by numerous small anastomosing tubes, lined with limonite and filled with clay. The removal of the softer material at exposed surfaces produces a vesicular or cavernous structure, and this, combined with the hardness and dark colour of laterite, has caused it to be mistaken for lava. A brecciated variety is produced by the collapse of the first formed superficial crust, and a subsequent re-cementing of the broken fragments by iron oxides.

There has been much discussion and considerable divergence of opinion as to the origin of laterite; but all investigators agree that it results from the decomposition of a great variety of rocks, whether of igneous, sedimentary, or metamorphic origin. Most of the Indian laterite is found overlying the basic lavas of the Deccan

plateau; but it also rests on gneiss and other rocks of the Peninsula. In West Africa it is found on schists, in East Africa on volcanic rocks and on gneiss, and in South Africa on slate, sandstone and granite. The generally accepted view is that laterite is a residual accumulation produced by the removal in solution of combined silica, lime, magnesia and the alkalis. There is also some metasomatic replacement by material brought from the underlying rock during periods of

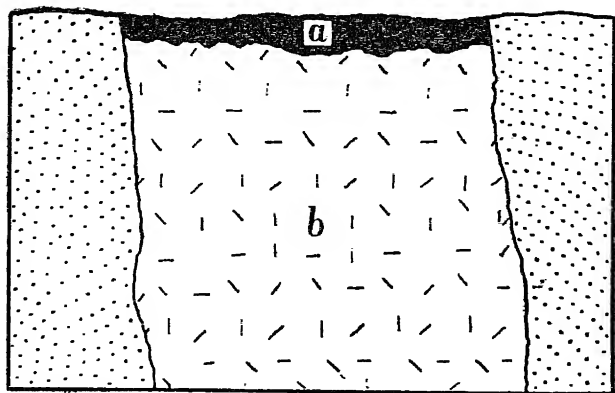


FIG. 22.—Diagram showing residual iron-ore deposit in Cuba: *a*, iron-ore; *b*, serpentinized peridotite.—After W. H. Emmons.

desiccation, by capillarity, aided perhaps by the rootlets of forest trees.

Laterite, when exceptionally rich in iron, may be of considerable economic importance. The iron ores of Cuba, on the high-lying plateau of Mayari and Moa, for instance, are residual mantles of lateritic material. Derived from the weathering of serpentine, they consist of hæmatite, limonite, a little magnetite, together with some aluminium hydroxide. Since the ore contains 20 to 30 per cent. of moisture and 13 per cent. of combined water, it has to be calcined in nodulizing

kilns before shipment. The nodulized ore averages 55 per cent. iron, 4.5 per cent. silica, 13 per cent. alumina, 1 per cent. nickel, and 2 per cent. chromium; phosphorus is below the Bessemer limit, and sulphur is negligible.

Lateritic iron-ore deposits, similar to those of Cuba, occur in the Philippines, in Borneo, and in West Africa. One in French West Africa is said to yield a nodulized product running over 60 per cent. iron.

The Lake Superior hæmatite deposits (Mesabi Range, etc.), which, as will be seen in a later chapter (p. 93), were precipitated as iron silicates, have after uplift and oxidation been concentrated by a leaching-out of the chert with which they are associated, and are therefore in a sense residual deposits comparable with those of Cuba.

The iron-ores of Bilbao in Northern Spain are in part residual deposits. The primary ores, formed by replacement of a Cretaceous limestone by siderite, have, under the influence of prolonged atmospheric weathering, been oxidized to limonite and hæmatite. Mixed with much residual clay these ores form a mantle covering the limestone up to 100 feet in thickness. The ores are low in phosphorus, the standard guarantee for best "rubio" being 50 per cent. iron, 8 per cent. silica, and under .02 per cent. phosphorus.

Manganese deposits are nearly always residual accumulations derived from manganese minerals sparsely distributed through igneous rocks and crystalline schists. The primary minerals are the silicates spessartite (manganese-garnet), rhodonite (manganese-pyroxene), tephroite (manganese-olivine); whereas the secondary minerals worked for manganese are chiefly pyrolusite ( $\text{MnO}_2$ ), psilomelane ( $\text{MnO}_2$ , with  $\text{H}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and Ba), and wad (a hydrated oxide of indefinite composition). These minerals occur in nodular and earthy deposits



in the zone of weathering. The chemical break-up of the manganese silicates produced a soluble bicarbonate of manganese which, in the first instance, deposited rhodochrosite ( $\text{MnCO}_3$ ), oxidation and hydration being a later stage in the process. Manganese deposits of this character are widespread in India, United States, Brazil, West Coast of Africa and many other places.

The nickel deposits of New Caledonia are also of residual origin. These ores are hydrated silicates of nickel (garnierite and genthite), and occur as earthy and brecciated masses in a ferruginous and clayey mantle overlying serpentine and peridotite. The average composition of the deposit is: ferric oxide, 69 per cent.; silica, 18 per cent.; nickel oxide, 1.64 per cent.; and water, 10 per cent.

A concentration of the heavier metallic constituents of the material shed from the outcrops of gold quartz veins and accumulated in their immediate neighbourhood gives rise to residual or eluvial deposits, which, in the case of gold, are sometimes of importance. They are characterized by the little-worn appearance both of the gold and of the gravel in which it is found. Rich placers of this nature occur in Alaska, often in close association with known auriferous beds. In dry countries the action of the wind in blowing away the lighter particles leaves a coarse detritus containing gold, of which the so-called *cement deposits* of Coolgardie in Western Australia are an example.

Wind action is also responsible for the final concentration of the diamantiferous gravels of South-West Africa. These concentrates of the diamond and its associated heavy and refractory minerals (garnet, olivine, chromite, etc.) are in fact residual deposits formed from earlier alluvial concentrations that have been traced back to an original source in volcanic pipes similar to those of Kimberley and Pretoria.

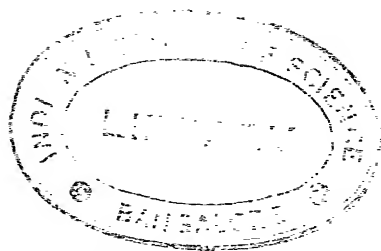
Residual gravels containing tinstone and wolfram occur on Bodmin Moor in Cornwall. These deposits, locally termed "head," consist of unrounded fragments of granite and vein quartz, together with wolfram and cassiterite. They are of pre-glacial age, and have escaped denudation by being frozen during a long period of their existence.

Similar residual gravels of pre-glacial age containing galena occur along the apex of veins of that mineral in North Wales, where they are sometimes 200 feet thick, and have been profitably worked.

Galena, originally occurring in veins and local disseminations in the "plateau limestone" of the Southern Shan States of Burma, has been set free by the erosion of a great thickness of the limestone and concentrated in the resulting mantle of residual red clays. These lead deposits have been worked for ages both by the Chinese and by the Shans for their silver content. The same residual clays contain local accumulations of iron-ore, which are also derived from eroded limestone.

Residual gravels containing zinc ores have been exploited as a source of zinc in Galicia. They have originated by the weathering of veins in Triassic limestone, chemical action on the soluble limestone having outpaced the mechanical erosion of the resistant minerals of the vein.

Much of the so-called tin alluvial in Malaya is in reality a residual deposit. Deep weathering has so disintegrated the granite and the overlying Triassic schists series that they can be worked by alluvial methods, that is to say, by sluicing, dredging, or other form of mechanical excavation.



## CHAPTER X

### ORE FORMATION BY CHEMICAL PRECIPITATION IN SEAS, LAKES AND SWAMPS

MANY deposits of iron ore owe their origin to precipitation in seas, lakes and swamps of iron derived from the decay of rocks in the zone of weathering. Iron goes into solution in this zone either by the oxidation of the sulphides of that metal, or by the breaking-up of ferro-magnesian silicates. Soluble iron compounds are also formed by the action of certain bacterial organisms present in the soil. These are the so-called iron bacteria of Winogradsky.<sup>1</sup> Reduced by their action to the ferrous state, the iron combines either with the organic acids of the humus or with the carbonic acid of the atmosphere to form a soluble bicarbonate.

On exposure to air, or in the presence of plant life, carbon dioxide is given off and iron carbonate is precipitated, as shown by the following reaction:



The ferrous carbonate rapidly oxidizes to ferric hydrate, and is deposited as *bog-iron* or *iron-pan*. A continuous layer of this *pan* consequently tends to form below insufficiently-drained clayey and peaty soils. The formation of ferric hydrate in stagnant swamp water, where ferrous carbonate is undergoing oxidation, may actually

<sup>1</sup> S. N. Winogradsky, *Botanische Zeit.* **46.** (1888), p. 261.

be seen in operation, and the iridescent films that form on such water are an indication that this reaction is taking place.

In the case of the Scandinavian *lake-ores* precipitation is effected by freshwater algæ, which flourish to a depth of 30 feet below the surface of the water. The deposit consists of a slimy mass of hydrated iron oxides and gelatinous silica, which on consolidation assumes an oolitic<sup>1</sup> or pisolitic<sup>2</sup> form. These ores are valuable, on account of their freedom from phosphorus, and are consequently worked even when only a few inches thick: they form very rapidly, a period of not more than thirty years being required to produce a workable deposit.

When the waters deposit their iron in the presence of much carbonic acid or of decaying organic matter, siderite ( $\text{FeCO}_3$ ) is deposited. In muddy waters the silt goes down with the iron carbonate, and in this way the material known as *clay-ironstone* is formed, in which the iron occurs as a ferrous carbonate. These clay-ironstones or *spathic ores*, as they are also termed, occur in the Coal Measures of the British Isles, and in those of Westphalia and North America, and are an important source of iron. The *black band* of the Coal Measures is a similar deposit, but differs from the bulk of the clay-ironstones in containing a high percentage of vegetable or peaty matter, sufficient, indeed, to furnish the fuel required to calcine it. On calcination it loses about 50 per cent. of its weight, the percentage of iron being correspondingly increased. Such ores represent what was once a carbonaceous mud in which ferrous carbonate was being precipitated.

The oolitic ironstones of England and the similar *minette* ores of Lorraine and Luxemburg, all of Jurassic

<sup>1</sup> Like fish-roe, from the Greek *oon*, an egg.

<sup>2</sup> Greek *pisos*, a pea.

age, constitute the greatest reserves of iron-ore in Europe. They form well-defined beds in a sedimentary series of sandstones, shales, and limestones of marine, estuarine, or deltaic origin. Although low in iron (20 to 40 per cent. metallic iron), a large lime content makes many of them practically self-fluxing, and having a high phosphorus content, they furnish a pig-iron admirably suited to the basic process of steel-making, while the residual slag constitutes a valuable phosphatic manure.

The ores consist of an aggregate of sand-grains, oololiths and fragments of fossils in a matrix of chamosite, carbonate of lime, or clay. The oololiths were originally chamosite (a green ferro-aluminium silicate of the chlorite class, having the formula  $3\text{FeO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{aq.}$ ) or limonite, but carbonation of the chamosite has in most cases resulted in the formation of siderite. The formation of oololiths presupposes shallow-water conditions in which a gentle agitation by waves or currents took place.

These iron-ores are worked in England on three horizons, namely, the Inferior Oolite (Northampton stone); the Middle Lias (the Cleveland ironstone and the marlstone); and the Lower Lias (Frodingham stone). The Northampton and Cleveland ironstones are chamosite mudstones and chamosite-siderite mudstones. The marlstone is a sideritic limestone, and the Frodingham stone is a limonite-oolitic ironstone. In the zone of weathering the sideritic ironstones are oxidized to limonite, a change in colour from green to red being characteristic. This change is generally accompanied by secondary enrichment due to the removal of carbonate of lime.

Some oolitic chamosite mudstones contain limonite both in the matrix and in the chamosite oololiths themselves. Such are the Clinton iron-ores of Alabama and Tennessee, and the Wabana iron-ores of Newfoundland.

The Clinton rocks are of marine origin and Silurian age. They consist of shales and calcareous sandstones, together with a small amount of limestone, in practically horizontal formation. The ore appears on three horizons, constituting distinct strata interbedded with the associated sediments. The lowest ore-bed rests on a thick bed of shale; it averages one foot in thickness and is of

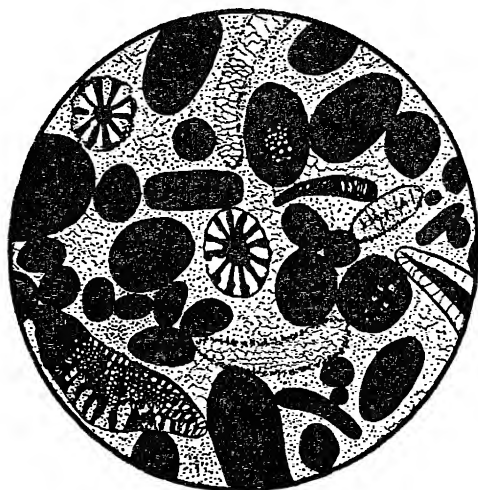
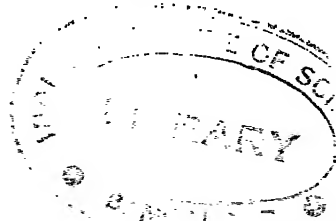


FIG. 23.—Photo-micrograph ( $\times 10$ ) of oolitic ironstone from Frodingham, Lincs. Opaque oolites of iron oxide and organic remains partly replaced by iron oxide in a groundmass of crystalline calcite.—After Rastall, *Geol. of the Metallif. Deposits*.

oolitic texture. Being of low grade, this ore is not worked. It is overlain by two feet of shale, on which rests an oolitic iron-ore of purple-red colour. This bed, two feet in thickness, has been traced and worked over an area of several miles, in which it maintains a remarkably uniform character both as to structure and composition. After an interval occupied by 20 feet of shales, it is succeeded by the third ore-bed, some two or three feet thick, but too lean to work. The Wabana rocks are shallow marine deposits of Ordovician age. In these



ores the ooliths consist of concentric shells of hæmatite and chamosite imbedded in a matrix of siderite. Algæ were probably responsible for the oxidation of chamosite to hæmatite. The ores occur in beds of from ten to thirty feet in thickness, interbedded with flat-lying sandstones and shales. They have been mined for over a mile under the sea.

The iron-ores of the Lake Superior region (Mesabi, Vermilion, Marquette, Menominee and many other so-called iron ranges), which now appear as high-grade hæmatites, are products of enrichment of chemically deposited sediments (of pre-Cambrian age), such as siderite and a hydrated ferrous silicate (greenalite—a mineral allied to glauconite), intimately interbedded with chert. On exposure to weathering (in pre-Cambrian times) the siderite and greenalite were oxidized to hæmatite and limonite, and concentration was subsequently effected by the leaching out of the silica of cherty bands. The bulk of the Lake Superior ore is a soft, porous, earthy hæmatite, partly hydrated, but deep burial and metamorphism have converted it locally into hard specular hæmatite.

The Buffelshoek-Gatkop hæmatite deposits of the Transvaal are of similar origin, having been formed by the leaching out of silica by oxygenated surface waters from banded ferruginous cherts and the breccias derived from them.

The bedded iron deposits of the Pretoria series in the Transvaal and in Griqualand West, which constitute immense resources of valuable iron-ore, are sediments of marine origin. They are composed of ooliths made up of closely placed shells of iron oxides (magnetite and hæmatite) and iron silicate (chamosite), which are probably of colloidal origin, it having been suggested that the chamosite is developed by diagenesis from colloidal ferrous aluminium silicate, and the hæmatite

and magnetite from colloidal ferric hydrate.<sup>1</sup> The iron was originally derived from the land areas bordering on the ancient ocean, on which the older banded iron-stones were doubtless exposed in numerous localities.

The metal content of the copper-bearing sandstones, so widely distributed throughout the world, owes its origin partly to precipitation and metasomatic replacement, partly to sedimentation. The prevalence of these deposits in the red beds of the Upper Carboniferous, Permian, and Trias formations indicates sedimentation in shallow lakes in desert regions where evaporation was rapid. The copper was, no doubt, leached out by meteoric waters rich in sodium chloride and calcium sulphate from earlier copper deposits in continental areas. Transported as sulphate or chloride, it was precipitated in inland seas or lakes and reduced to sulphides by decaying organic remains. The replacement of tree-trunks and other plant remains as well as of the cementing material of the sandstones by chalcocite is a characteristic feature of these deposits.

The accumulation of cupriferous detritus while sedimentation was in progress was, no doubt, a factor of the concentration in some cases, but such material would of course be subsequently modified by the circulation of the ground-waters. Associated minerals are calcite, gypsum and barytes. In the zone of weathering the copper ores are oxidized to the green and blue carbonates—malachite and azurite.

Copper sandstones of the character described are found west of the Urals in the Russian Permian of Orenburg, in the Lower Permian of Bohemia and Würtemberg, at Alderley Edge in Cheshire, in the Permian of Texas, New Mexico and Colorado, and in the well-known deposits of Coro-Coro in Bolivia, and

<sup>1</sup> P. A. Wagner, "Iron Deposits of the Union of South Africa," *Geological Survey S.A., Mem.* 26. (1928), p. 119.

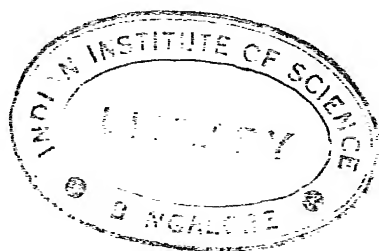


of Boleo in Mexico. The similar copper sandstones of Katanga in the Belgian Congo and of the Kirghiz steppes near the Altai Mountains are believed to be of Palæozoic age.

Many of these copper deposits contain vanadium—usually as vanadinite or roscoelite (vanadium mica)—no doubt derived by the concentrating action of meteoric waters from small quantities of the metal widely disseminated in minute quantities in the ancient land areas.

The copper-shale (Kupferschiefer) of Mansfeld in Saxony deserves special mention. The copper-bearing bed, less than two feet in thickness, is in the middle division of the German Permian, that is, it lies between the Zechstein (magnesian limestone) above and the Rothliegendes below. The bed is a black shale with abundant plant and fish remains and richly impregnated with finely divided sulphides of copper (chalcopyrite, bornite and chalcocite), iron (pyrites), lead (galena) and zinc (blende). These minerals occur as minute isolated grains, completely surrounded by clay and bituminous material, and have evidently been formed by the precipitation and subsequent reduction of copper and other metallic compounds in a shallow inland sea in the presence of much decaying organic matter and probably with the aid of bacterial growths.

The lead-bearing sandstones of Commern and Mechernich in Rhenish Prussia must also be mentioned here. In this case the ore minerals are galena and cerussite, together with a little chalcopyrite and barytes. The galena sometimes occurs in large crystals or knotty concretions enclosing grains of sand.





## CHAPTER XI

### THE FORMS OF ORE DEPOSITS

ORE deposits, although they occur in a multitude of different forms, may for convenience be divided into two classes, namely, (1) those that have a tabular or sheet-like habit, and (2) those that are non-tabular.

**Tabular deposits** are either *beds of sedimentation* or *precipitation*, and form a part of the general stratification of the country, or they are *veins* or *lodes* that owe their origin to the filling of fissures or to the replacement of the country-rock along the path of the mineral-bearing solutions. As a rule, veins and lodes cut across the stratification; but occasionally they conform with the strike and dip of the formation in which they occur and are then termed *bedded veins*. Where there are a number of parallel veins, irregularly connected, the system is known as a *composite vein* or *lode*. The term *linked veins* is used in a similar sense. A system of closely spaced and parallel veins is spoken of as a *sheeted zone*. A *gash vein* is a term generally used to describe the fillings of joints in limestone that do not extend upward or downward beyond a given bed of the limestone. Naturally the nature of the country-rock determines the character of the fissuring. In a tough rock the fissures are usually clean-cut; in a more easily shattered rock they are irregular and more numerous. Consequently a vein which is uniform and continuous in a rock of the former class may, on passing into a rock

of the latter class, be split up into several branches, or even into a network of small veins. A change of another sort is illustrated by the lead-zinc veins of the mining district of Derbyshire. The Carboniferous limestone is here traversed by sheets of basaltic lava, locally known as *toadstone*. Veins that are strong and productive in the limestone shrink to barren fissures on passing into the igneous sheets, but recover their productivity on

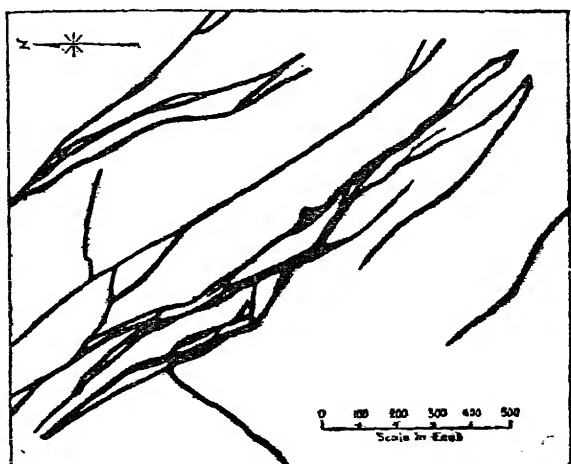


FIG. 24.—Diagram showing linked veins.—After Spurr, *The Ore Magmas* (1923), p. 326.

re-entering the limestone. This suggests that the word “toadstone” is a mining term derived from the German *todstein* (dead or barren stone).

A similar change was described by Theodore Scheerer<sup>1</sup> and by Hermann Müller<sup>2</sup> in the silver-lead-copper veins of the Freiberg mining district of Saxony. These are numerous and productive in the lower grey biotite-gneiss of the district; but are fewer and less

<sup>1</sup> *Zeitsch. der deutsch. geol. Gesell.*, 14. (1862), p. 82.

<sup>2</sup> *Die Erzgänge des Freiburger Bergrevieres*, Leipzig (1901), pp. 280-1.

productive in the upper grey gneiss, and almost entirely absent in the overlying red muscovite-gneiss and granulite.

Although veins are tabular deposits in a general sense, their bounding surfaces are rarely strictly parallel, for, except in the case of fissure fillings, there is more often than not only one well-defined wall, and in some cases none at all. In mining, however, it is usual to speak of the hanging wall and the foot wall of a vein to distinguish the limits of the workable deposit, whether they are well-defined or not.

Where the filling of the fissure has been followed by differential movement, one or both of the walls are usually smooth and polished (*slickensides* or *friction-planes*). Slickensides vary according to the nature of the rock; if one of the rocks in contact is softer than the other, the surface of the softer becomes planed, grooved and striated, the striæ indicating the direction of movement; if both rocks are hard, the surfaces are highly polished and glassy; and when carbonaceous matter is present, they are covered with a film of graphite, or of pyrites when that mineral is present.

Between the actual vein-filling and the wall of the country-rock there is often a thin selvage of comminuted rock or clay known as *flucan*, *gouge*, or *pug*. Sometimes the filling is entirely made up of pieces of the country-rock that have been broken off during the formation of the fissures (*fault-breccia*, *crush-breccia*), and these are often cemented by the ore itself. Such veins are termed *brecciated veins* or *lodes*.

Sometimes the vein appears to send off branches or *spurs* into the country-rock, and occasionally large pieces of the latter are completely surrounded by branches of the vein. Such isolated pieces of the country-rock are termed *horses* by the miners. They are formed by the reopening of filled fissures involving both vein

and country-rock, followed by a fresh period of mineral deposition.

Where the fissuring was accompanied by dislocation, as is mostly the case, the veins have a lenticular character along both the strike and dip. This lenticular character is due to the differential movement of curved

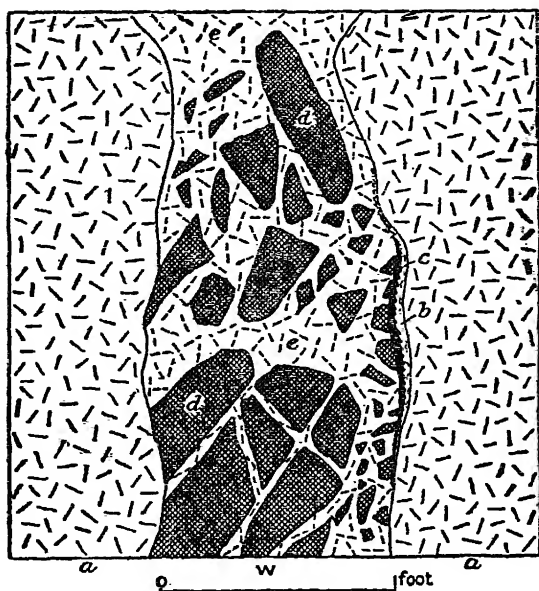


FIG. 25.—Cross-section of brecciated vein in Mendota mine, Colorado: *a*, granite walls; *b*, quartz; *c*, pyrites; *d*, blende; *e*, comminuted granite.—After Spurr and Garrey. From W. H. Emmons's *Prin. of Econ. Geol.*

or warped surfaces (see Fig. 26). Between the lenses the fissure is often so constricted that no ore occurs at all. When the axes of the lenses lie in one plane the lenses are usually connected by stringers; when they lie *en échelon* they are usually disconnected.

Not every part of a vein is equally mineralized. The pay-ore may occur in *streaks*, *spots*, *nests* or *bunches*.

But, besides this irregular distribution, the pay-ore is often confined to certain well-defined bands separated by low-grade material or even by barren gangue: these are termed *ore-shoots*. If they have a tendency towards the horizontal, they are distinguished as *ore-courses* or *ore-horizons*; if, on the other hand, they tend towards

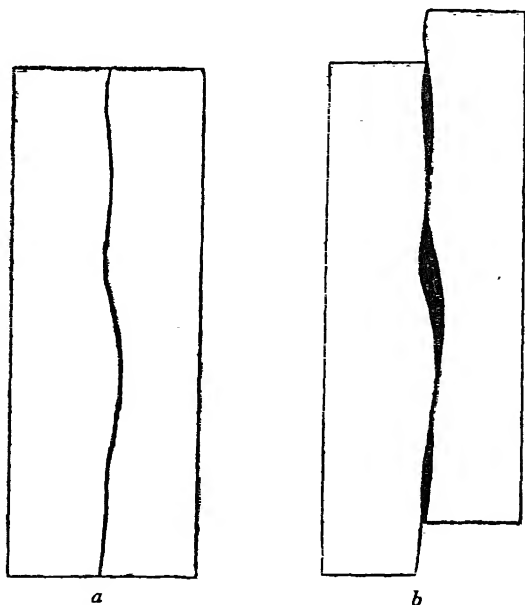


FIG. 26.—Diagrams illustrating the formation of lenticular cavity fillings produced by the differential movement of warped surfaces: *a*, before movement; *b*, after movement and ore deposition.

the vertical they are known as *columnar ore-shoots* or *chimneys*. But the term ore-shoot is not restricted to the occurrence of high-grade material in a low-grade matrix; it is also applied to the development along a fissure of lenticular bodies of pay-ore, separated by barren country-rock. Irving<sup>1</sup> proposes to call this latter class of ore-shoot *shoots of occurrence*, and to use the term

<sup>1</sup> *Economic Geology*, 3. (1908), pp. 132-154.

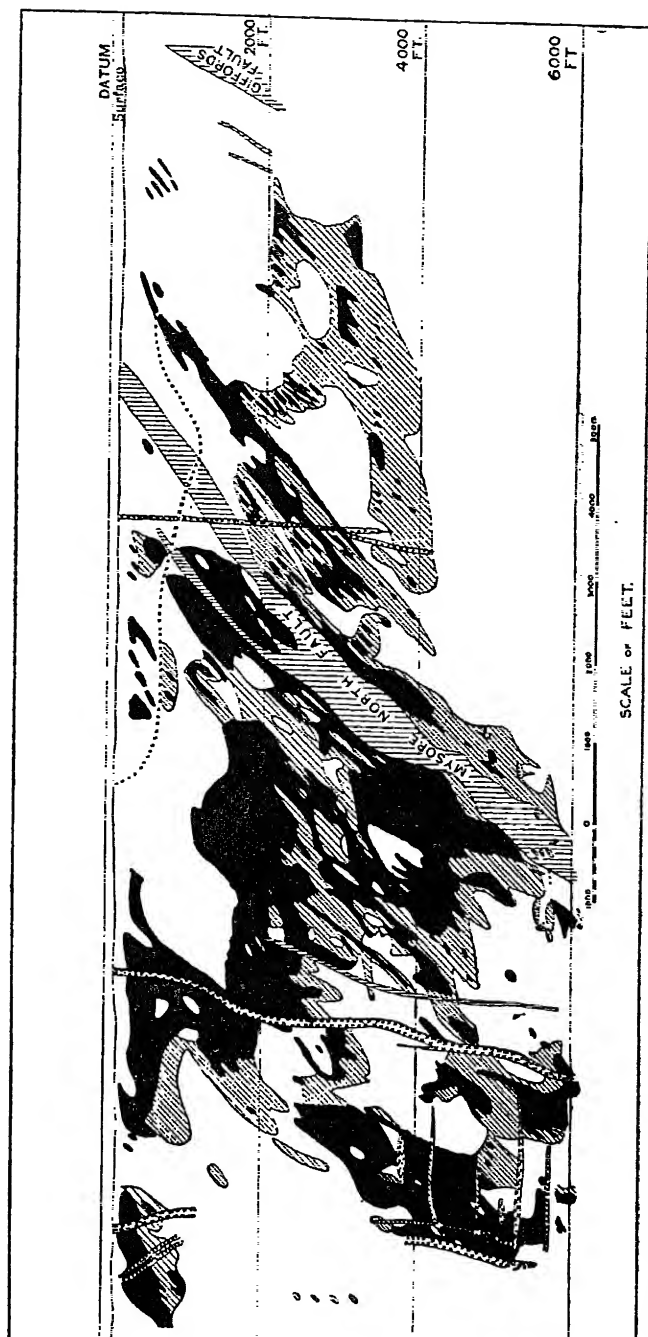


FIG. 27.—Section showing ore-shoots on the Champion lode, Kolar goldfield, Mysore. Payable ore shown black; unpaid quartz by diagonal lines.—After T. Pryor.

*shoots of variation* for the former. Shoots of variation are usually distinguished from shoots of occurrence by gradual shading away of the values towards their boundaries. It is not always easy to determine the

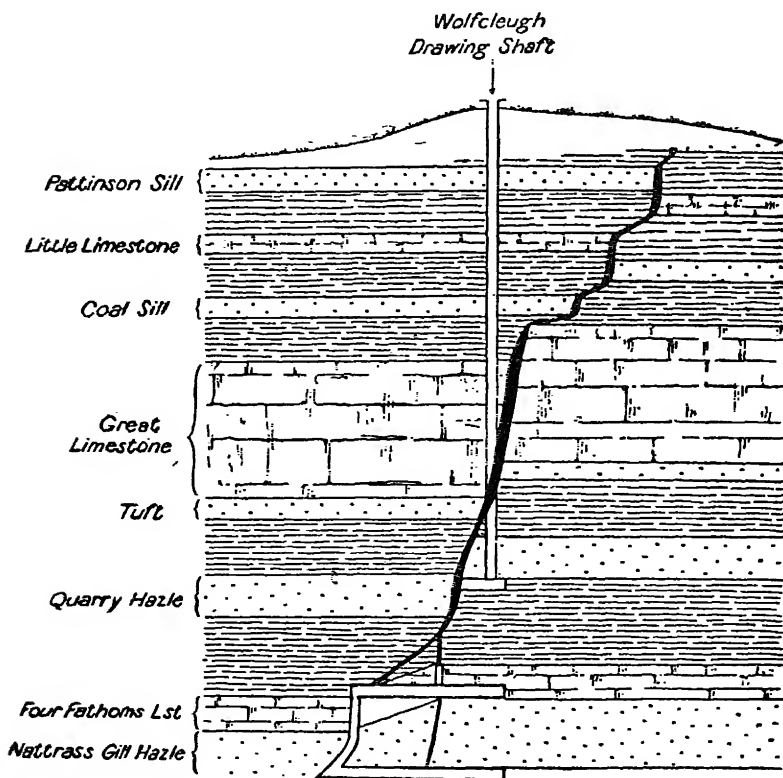
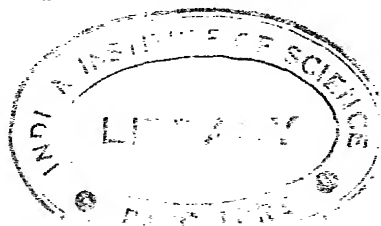


FIG. 28.—Section of Wolfcleugh mine, Weardale (scale 100 ft. to 1 inch), showing lead-zinc vein cutting and faulting Carboniferous limestone. Note the variation in size of the vein as it passes through limestone and shale beds respectively.—From *Special Rep. Geol. Surv. of Great Britain*, 26. (1923), p. 9.

cause of the variation in values; but in some cases it may be traced to the influence of the wall rock. Thus it is found, even in veins that are true fissure fillings, that the valuable mineral is often restricted to or attains its best development in those portions of the vein that





traverse rocks of a certain type. If the fissure dips at a high angle and crosses a formation composed of horizontally bedded rocks, or beds inclined at a low angle, the repetition of the favourable country may cause a series of parallel *ore-courses* or *ore-horizons*. On the other hand, where several parallel fissures cross a formation that encourages ore deposition, a series of ore bodies may be formed, a phenomenon known to miners as *ore against ore*.

Ore-shoots are in some cases found at the intersection of two or more veins. In these cases the enrichment may be due to the arrest of circulation at the point of junction, especially if the circulations along the fissures are in opposed directions, or it may be due to the mingling of waters of different composition and temperature.

Although, speaking generally, ore-shoots have irregular boundaries, in the majority of cases there is a rude parallelism between their two bounding surfaces. The angle made by these bounding surfaces with the horizon is termed the *pitch* of the ore-shoot, and is to be distinguished from the *dip* of the vein, which is measured in a plane at right angles to that in which the pitch is measured.

**Non-Tabular Deposits.**—The non-tabular deposits vary greatly in shape and size. They may be large irregular masses or small pockets of solid ore, or they may be *stockworks*, i.e. reticulated masses in which a multitude of small veins traverse a portion of the country-rock. Of exceptional character are *saddle-reefs*, which are ore bodies filling the cavities at the crests of anticlines, and *chimneys* or *pipes*, which are ore bodies having a rudely circular or elliptical cross-section with considerable vertical extent.

Examples of large irregular massive deposits are the iron ore segregations formed by magmatic differentia-

tion. They were described in detail on pp. 26-28. It therefore only remains to give examples of stockworks, pipes and saddles. Stockworks are common in the tin deposits of Cornwall, Saxony and Malaya. At the Mulberry mine near Bodmin, described by Le Neve Foster, a mass of slate (killas) is traversed by a network

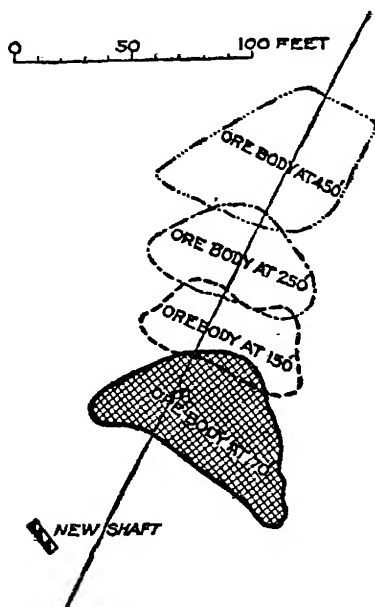


FIG. 29.—Plan of Bull-Domingo mine, Colorado, showing shape of pipe-like ore body at different levels.—After S. F. Emmons, 17th Ann. Rep. U.S. Geol. Surv.

of innumerable stringers of cassiterite varying in width from a fraction of an inch to 4 or 5 inches; the stringers are mostly inclined at a high angle, and are only 2 or 3 inches apart; the whole stockwork is 300 yards long by 30 wide, and of unknown depth. The well-known tin stockwork of Altenberg in Saxony, which is 3,000 feet in length and breadth and of unknown depth.

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consists of a mass of granite altered to greisen and traversed by innumerable small veins of cassiterite (*Zwittergestein*). Examples of Malayan stockworks are the Rahman and the Bruseh mines in the western tin belt of the peninsula. Good examples have also been described in the gold quartz formation of Pahang.<sup>1</sup> In

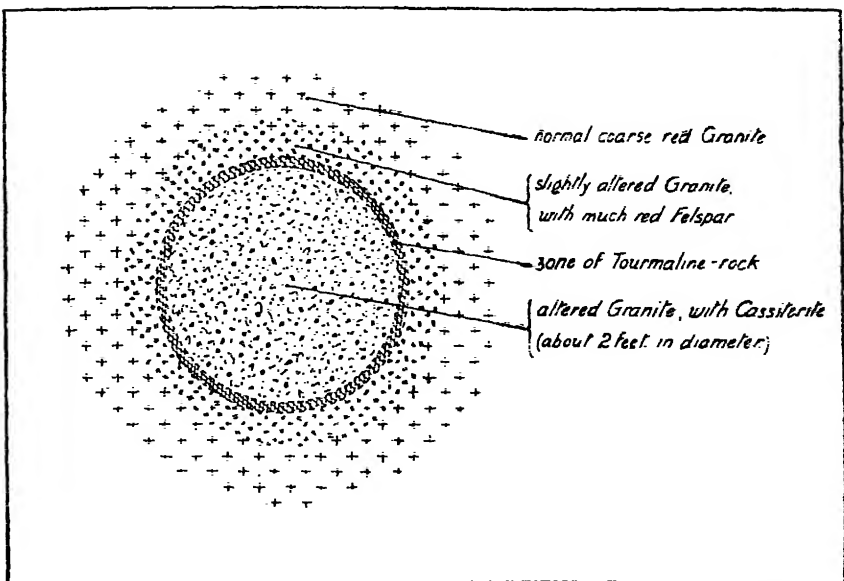


FIG. 30.—Diagrammatic section of small cassiterite pipe in granite at Zaaiplaats Transvaal.—From *Memoir No. 4, Union of S.A. Geol. Surv.*

certain areas black Palæozoic slates are seamed with narrow veinlets of quartz. An infinite number of these intersect and anastomose in such manner as to constitute the whole rock zone a workable deposit, as in the well-known Raub Mine.

Two varieties of pipes are well known, namely the diamond pipes of South Africa and the tin pipes of Malaya and the Transvaal. The former are the throats

<sup>1</sup> H. M. Becher, *Quart. Journ. Geol. Soc.*, **49**. (1893), p. 84.

of volcanic explosion vents, the diamond-bearing *blue ground* filling them being the fragmentary material brought up from below in the course of the volcanic eruption. The origin of the tin pipes is quite different, being due to a pneumatolytic alteration of the granite in which they occur, and the well-known occurrence

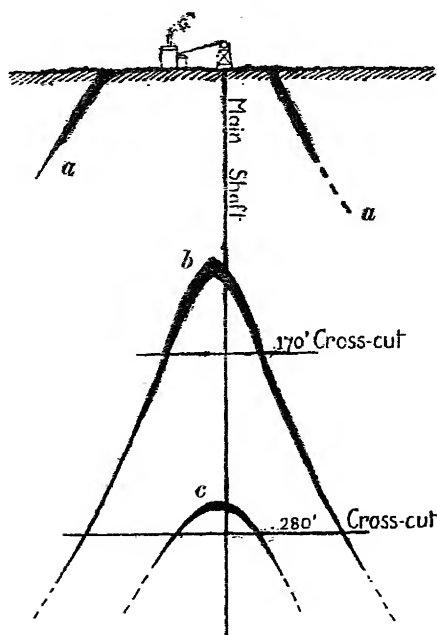


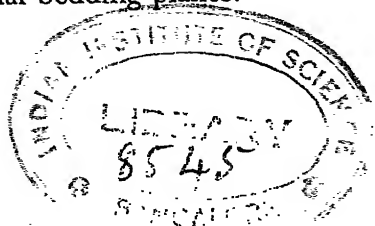
FIG. 31.—Section showing saddle-reefs at the New Chum mine, Bendigo, Australia: *a*, legs of a saddle; *b*, the "cap," or apex, of a second saddle; *c*, a third saddle.—After T. A. Rickard.

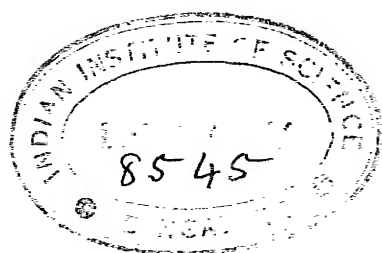
at Zaaiplaats in the Bushveld igneous complex of the Transvaal may be described as an example. The pipes are roughly cylindrical bodies of altered granite, carrying cassiterite, tourmaline and other pneumatolytic minerals. At right angles to the main axis they have circular, oval or elliptical sections, whose diameters vary from a few inches to several feet. Frequently neighbouring pipes, while quite distinct at the surface, are

found to unite in depth to one body, and are therefore simply branches given off from a main trunk below. A zonal arrangement indicates an action of the mineralizing vapours from the centre outwards. Near the margin of the pipes the felspar of the granite shows signs of alteration, its red colour being deepened; the red zone is generally succeeded inwards by an aureole of tourmaline-quartz rock, in the centre of which occurs the actual cassiterite-bearing mass.

While in the smaller pipes the cassiterite is fairly uniformly distributed throughout this central portion, in the larger and richer bodies a marginal portion sometimes contains over 70 per cent. of cassiterite. Although usually the pipes are quite independent, there are cases in which they appear to be connected with fissures and then resemble lenticular swellings on a line of fissuring. The ore body is a true replacement deposit formed from the granite by pneumatolysis.

The saddle-reef type of ore deposit is best illustrated by the gold mines of Bendigo in Victoria. Here the Ordovician strata, consisting of slates and sandstones, have been folded into a many times repeated series of anticlines and synclines, and auriferous ore bodies have been formed by the deposition of quartz in the resulting fractures at the crests of the anticlines. The saddle-reefs occur one above the other as disconnected ore bodies, in what is known to the miners as the "centre country." Thus in working the New Chum and Victoria mines thirty saddle-reefs were successively passed through down to a depth of over 4,000 feet in the first-named case. The axes of the anticlines have a pitch to the east, and the ore body may be followed along this axial line in some cases for miles. But in the direction of the limbs or legs of the anticlinal fold the ore body gradually narrows to a mere thread of quartz along the parting of the original bedding planes.







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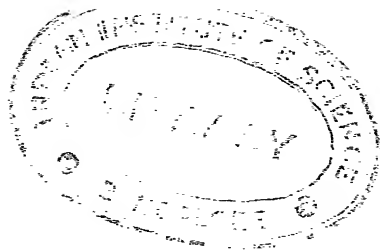
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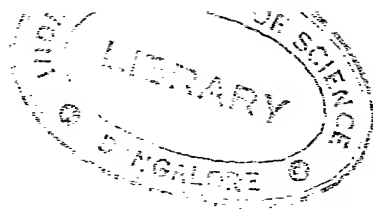


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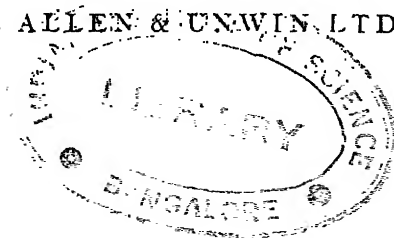
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